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(54) **METHODS OF PREPARING TISSUE OF A PATIENT TO RECEIVE AN IMPLANT**

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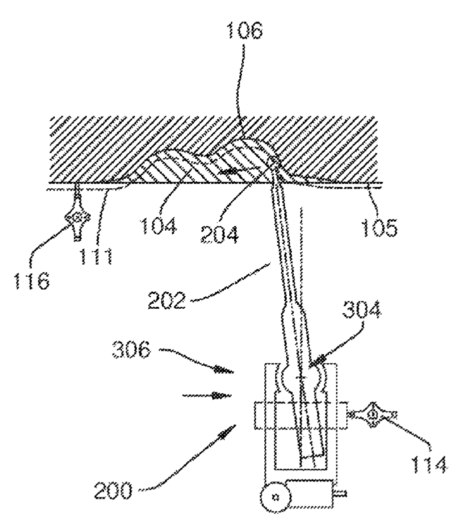
(57) **ABSTRACT**

Methods of removing tissue from a patient during a surgical procedure, such as for preparing a spine of a patient to receive an implant during a fusion procedure. A working portion of an instrument is moved with actuators relative to a hand-held portion in at least three degrees of freedom including pivoting in pitch and yaw about a pivot. The working portion is translated while the hand-held portion is manually grasped and moved during the surgical procedure. The working portion is rotated with a drive mechanism to remove a volume of the tissue of the patient with a cutting accessory of the working portion. The actuators may move the working portion to substantially maintain the cutting accessory in a desired relationship to a virtual boundary defining the volume of the tissue to be removed. A position of the cutting accessory relative to the virtual boundary may be determined and tracked.

9 Claims, 84 Drawing Sheets



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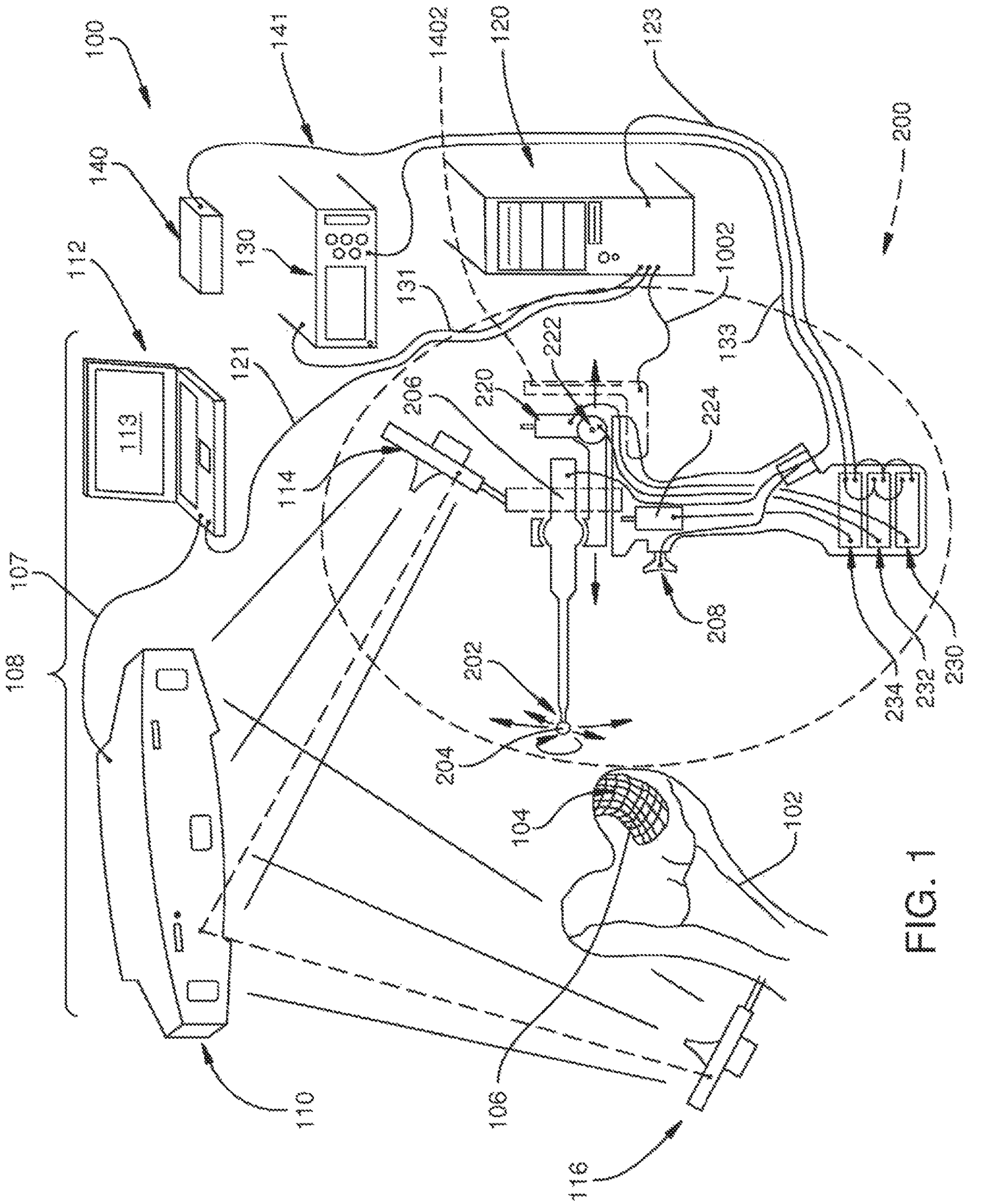
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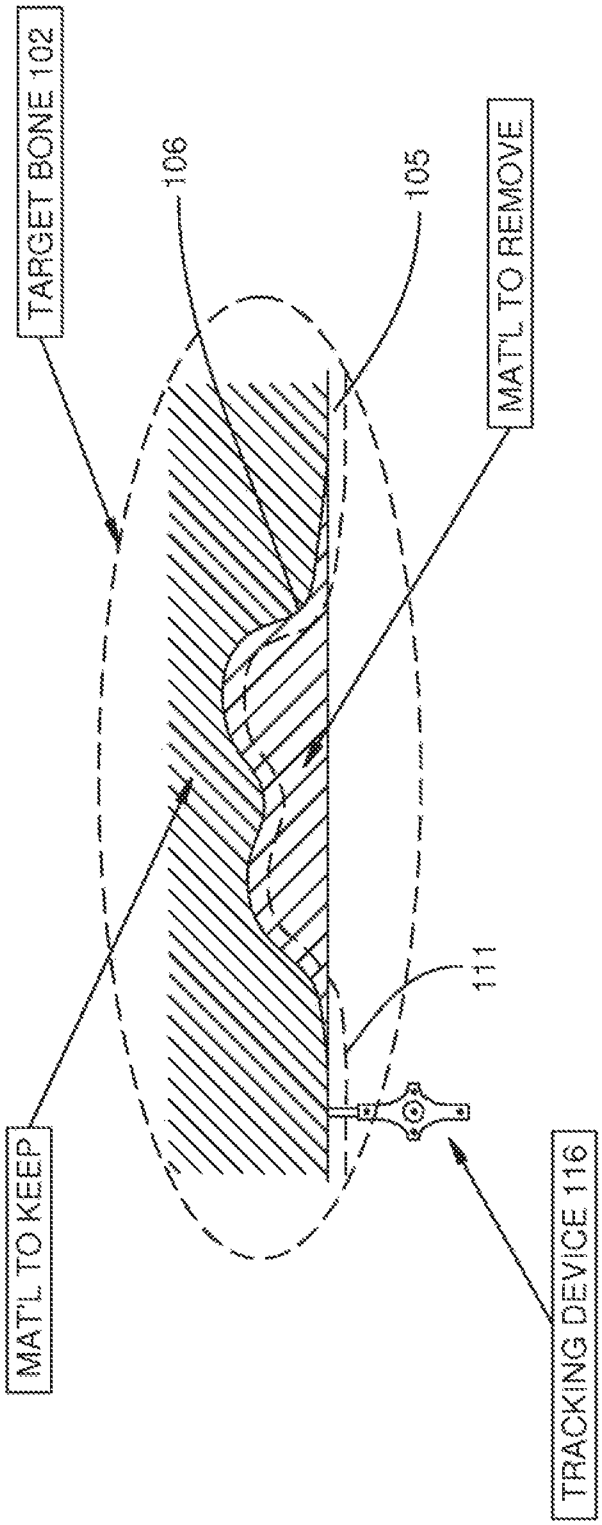
FIG. 1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MAT'L TO REMOVE
111
MAT'L TO KEEP
TRACKING DEVICE 116

FIG. 1A

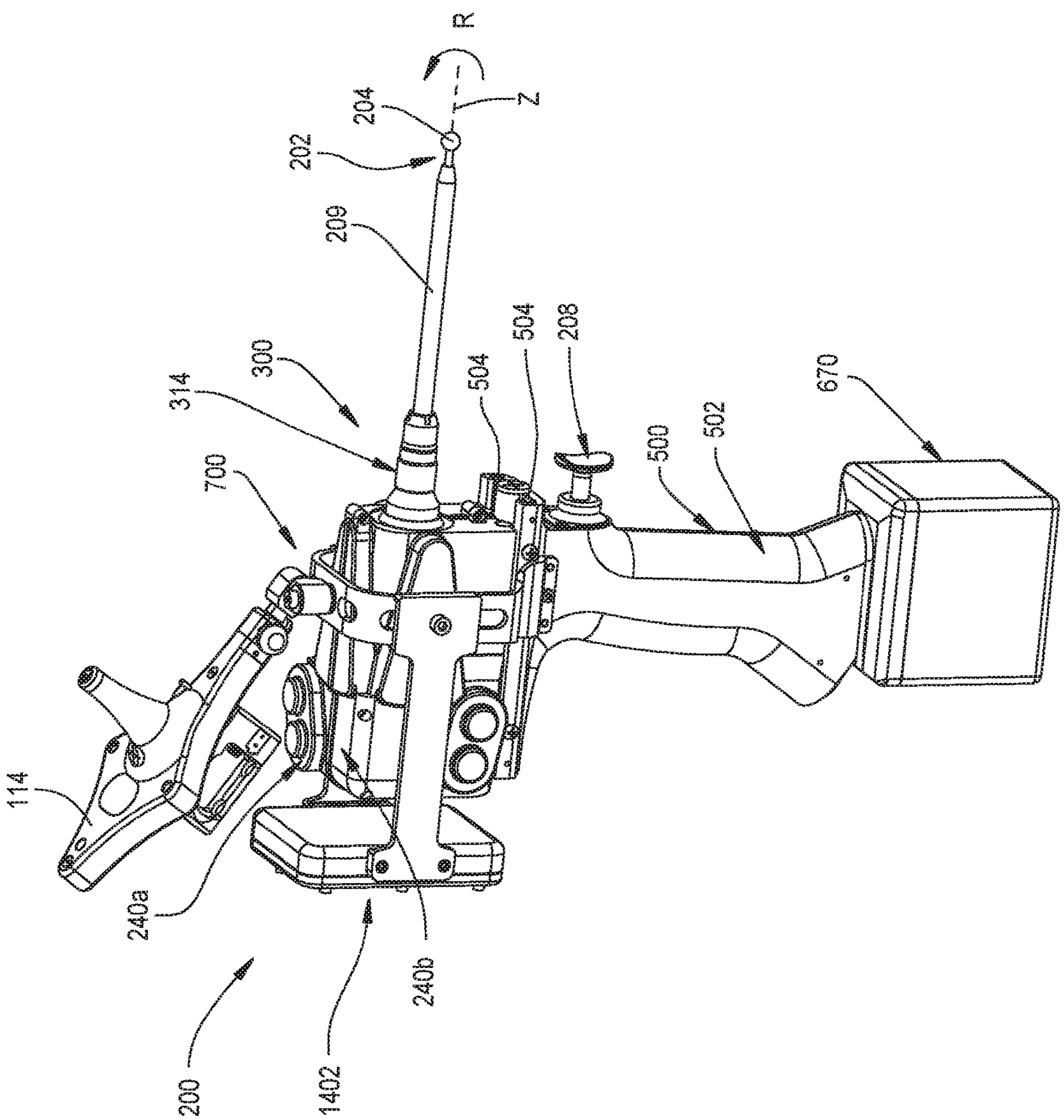
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FIG. 2

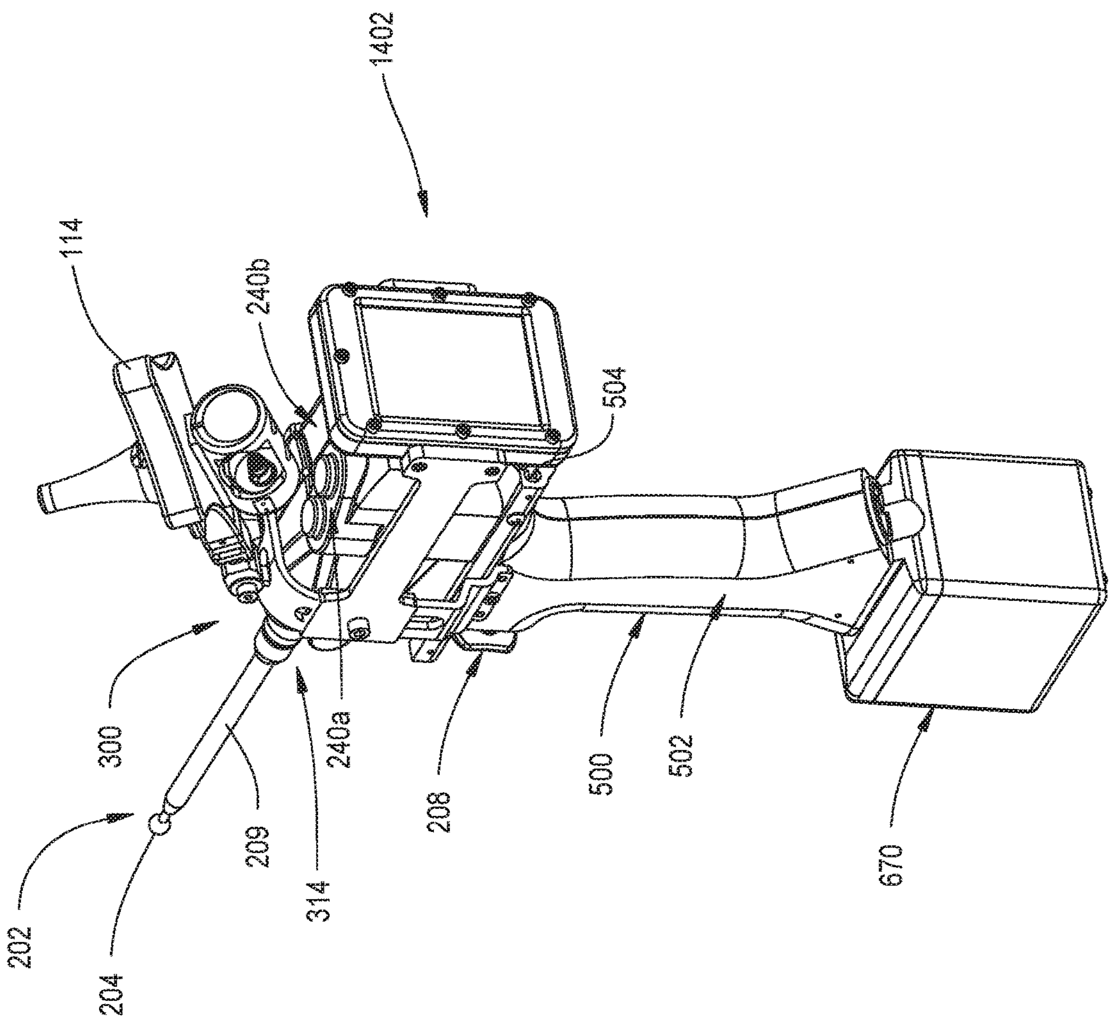

FIG. 2A

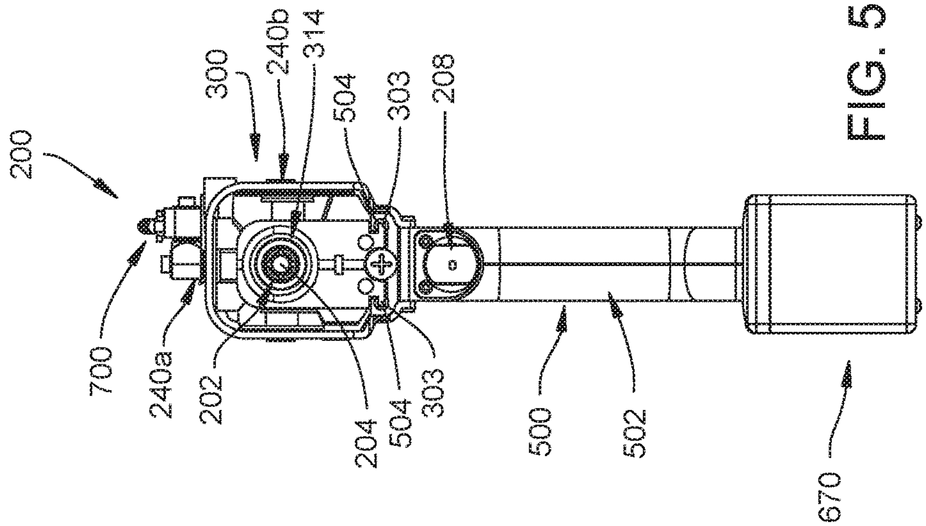

FIG. 5

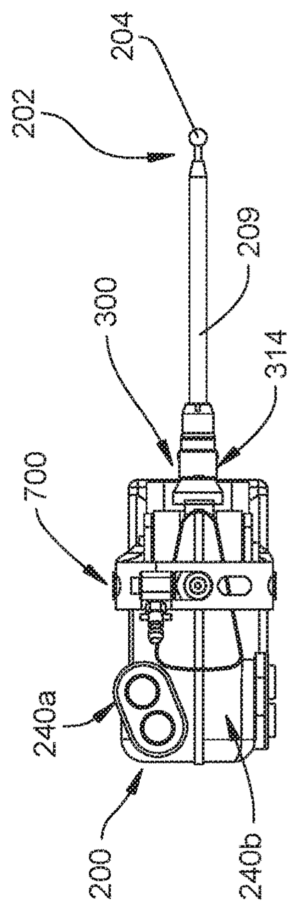

FIG. 4

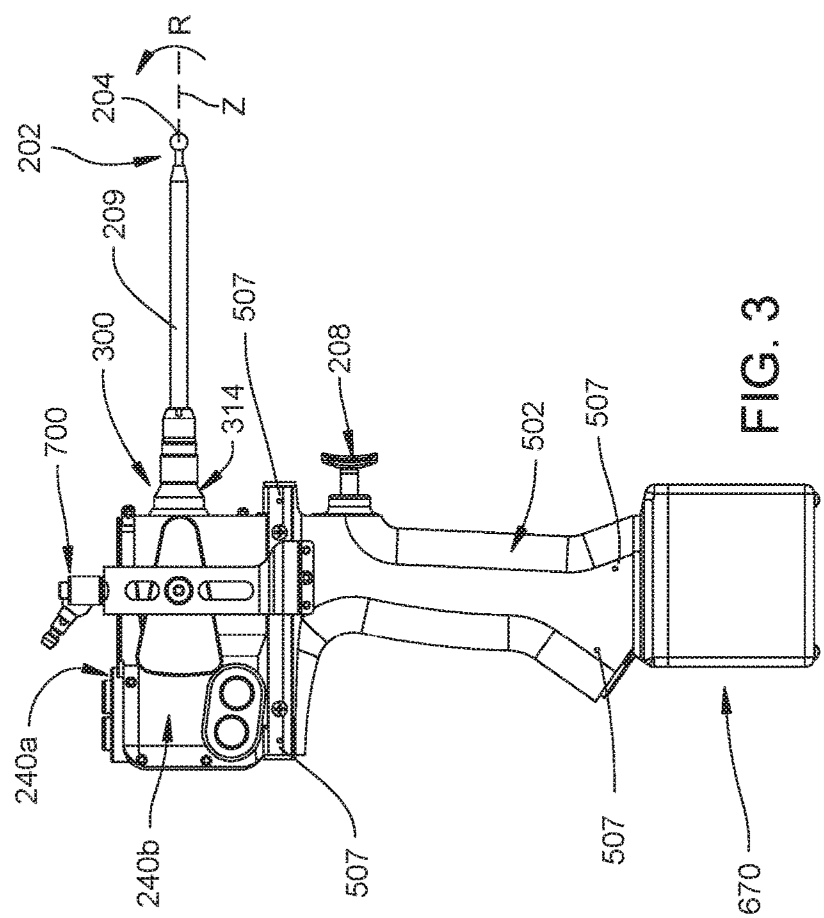

FIG. 3

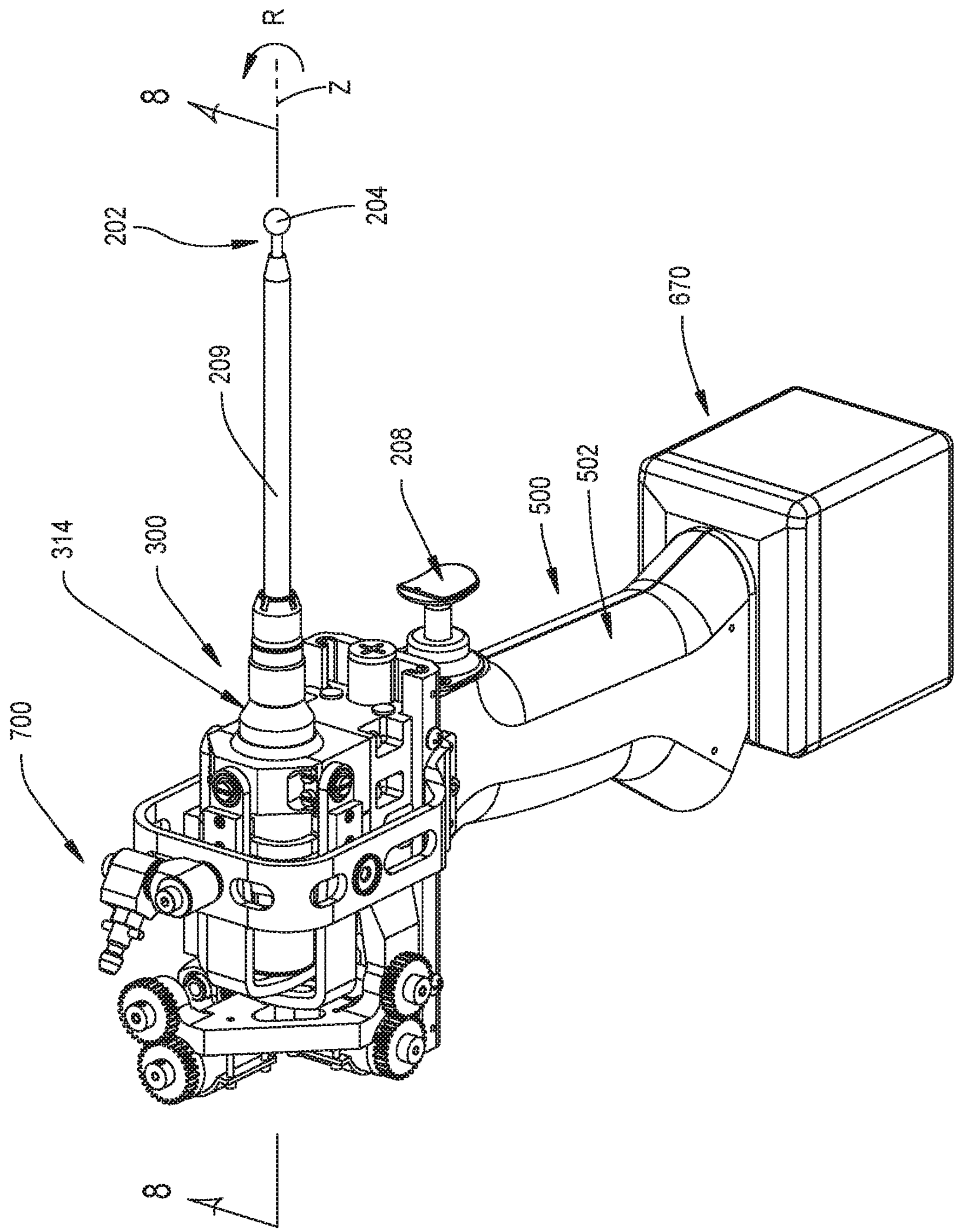

FIG. 6

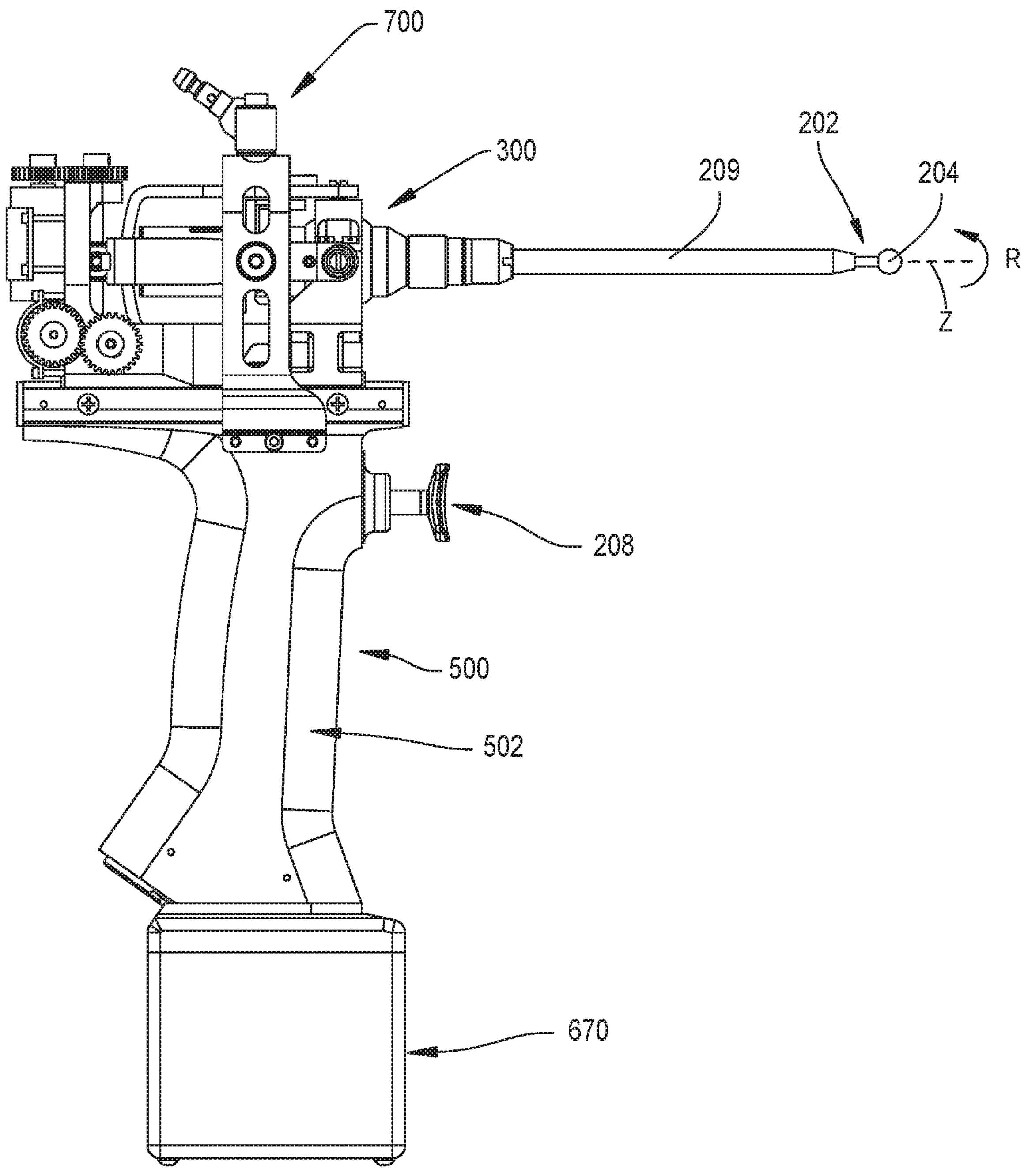

FIG. 7

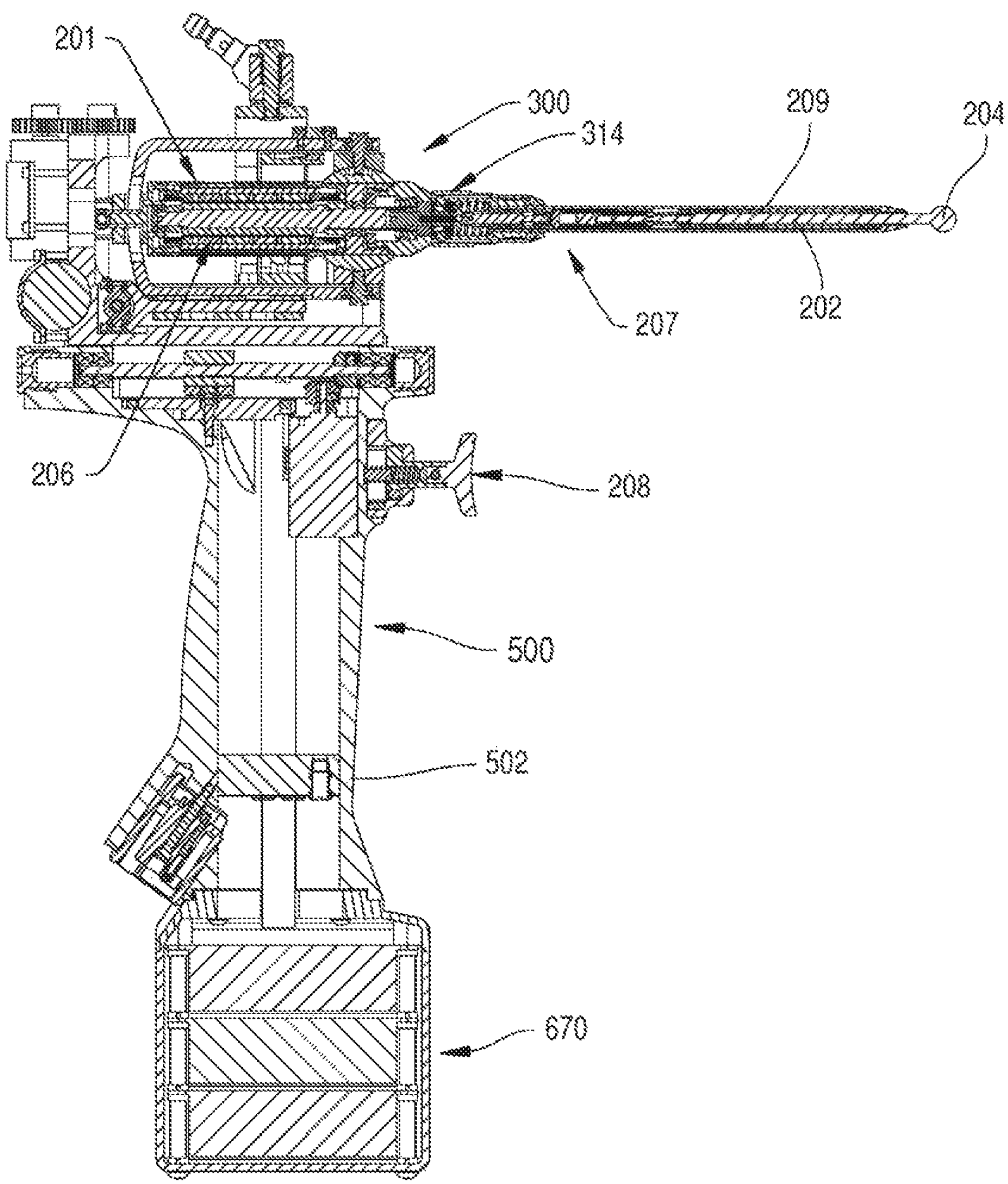

FIG. 8

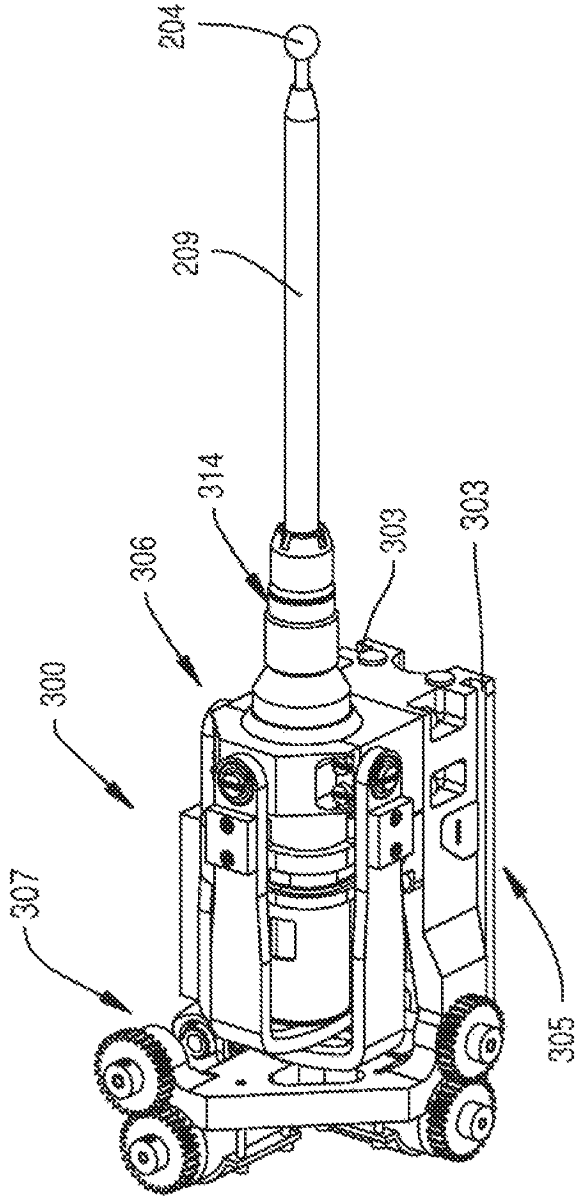
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FIG. 9

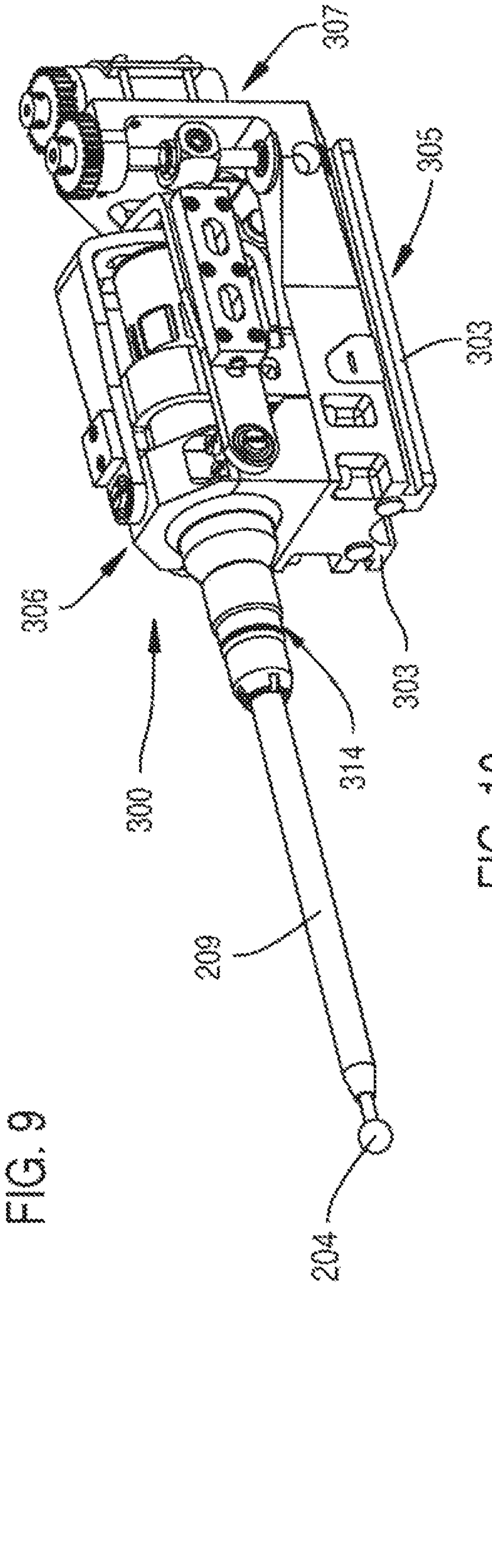
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FIG. 10

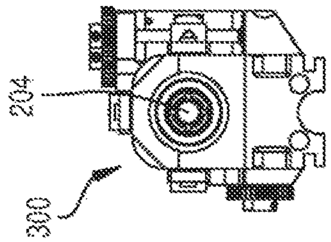

FIG. 15

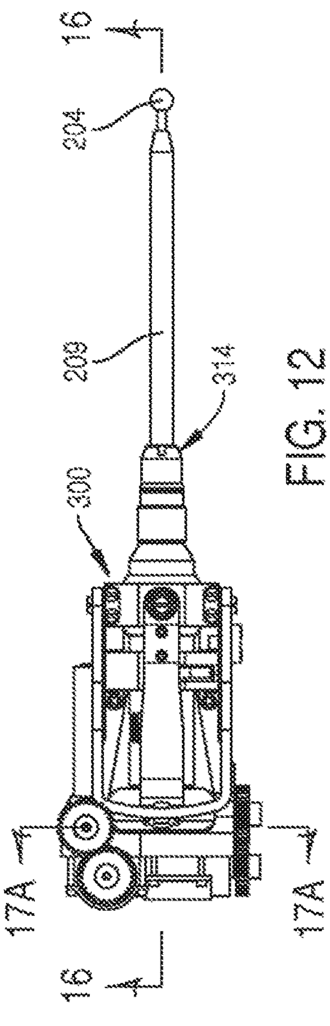

FIG. 12

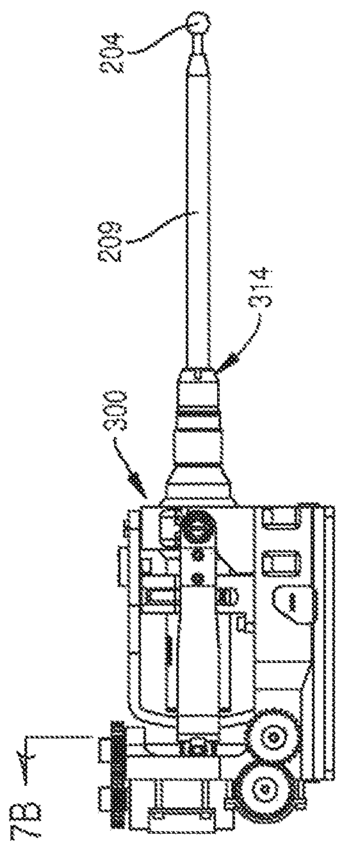

FIG. 11

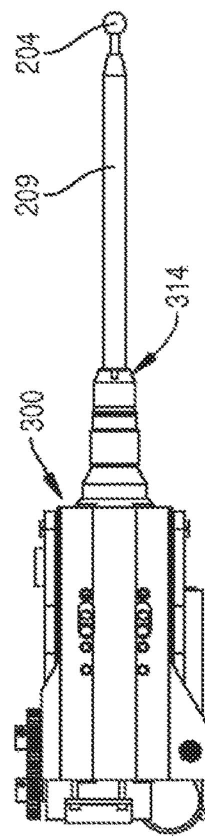

FIG. 13

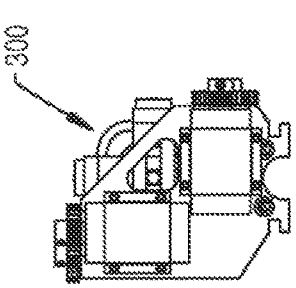

FIG. 14

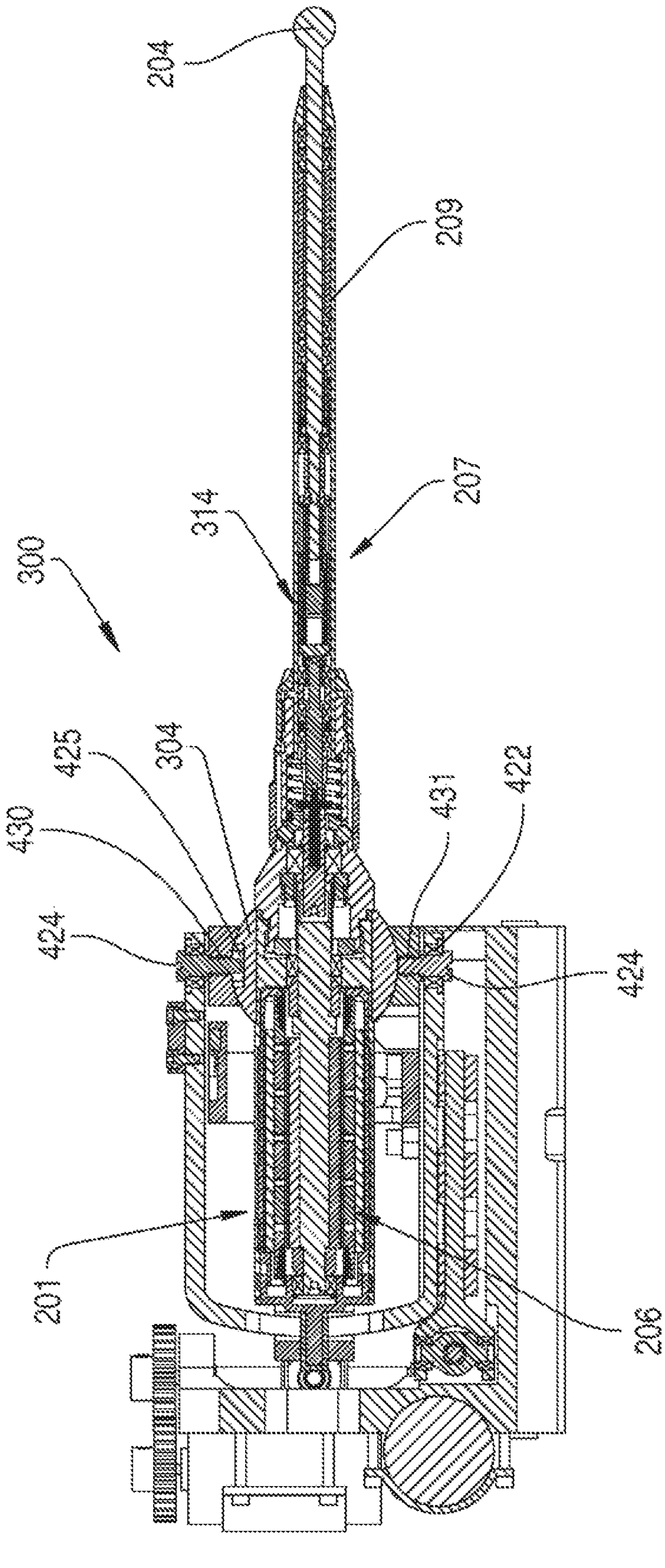

FIG. 16

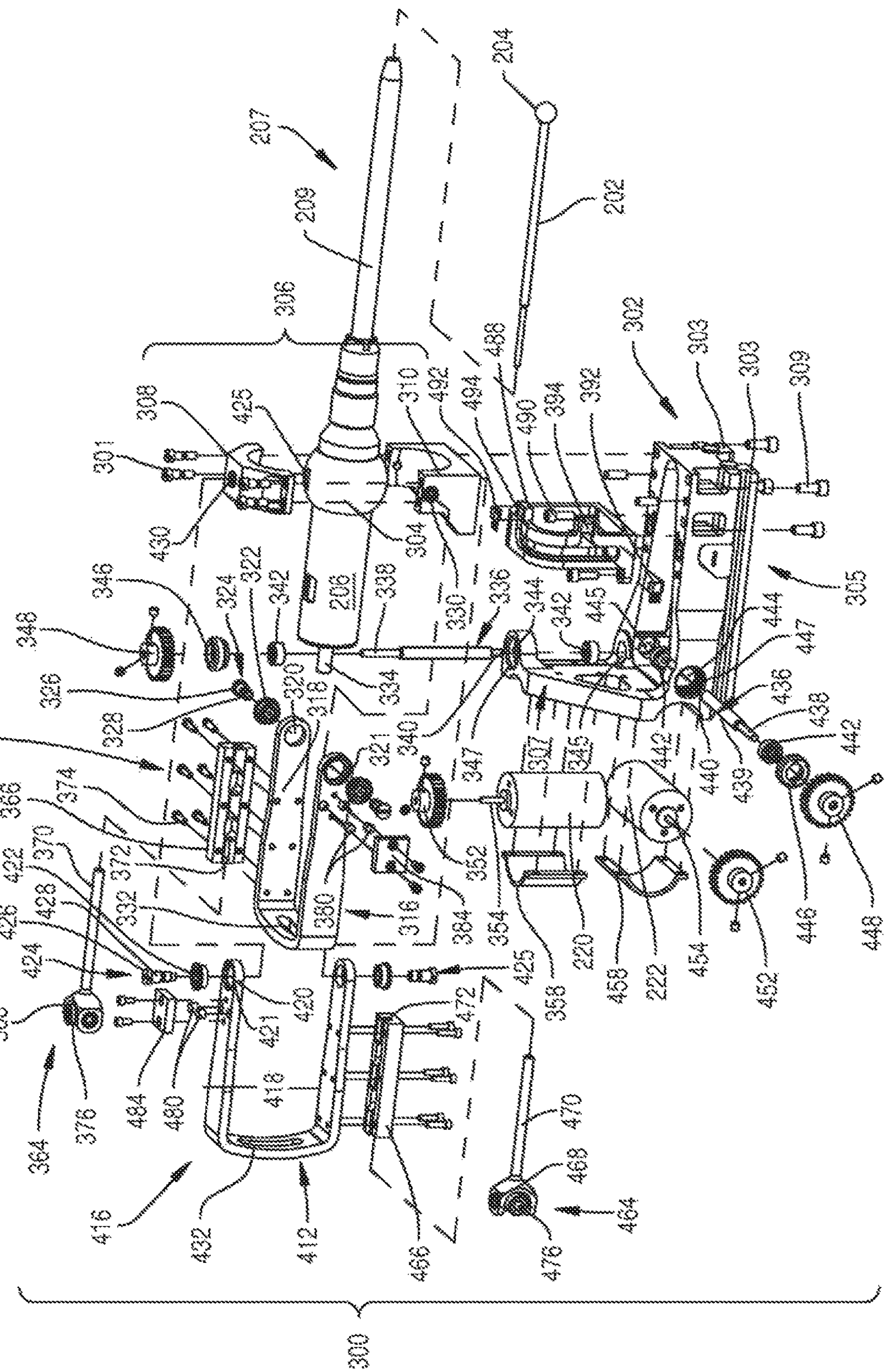
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FIG. 17

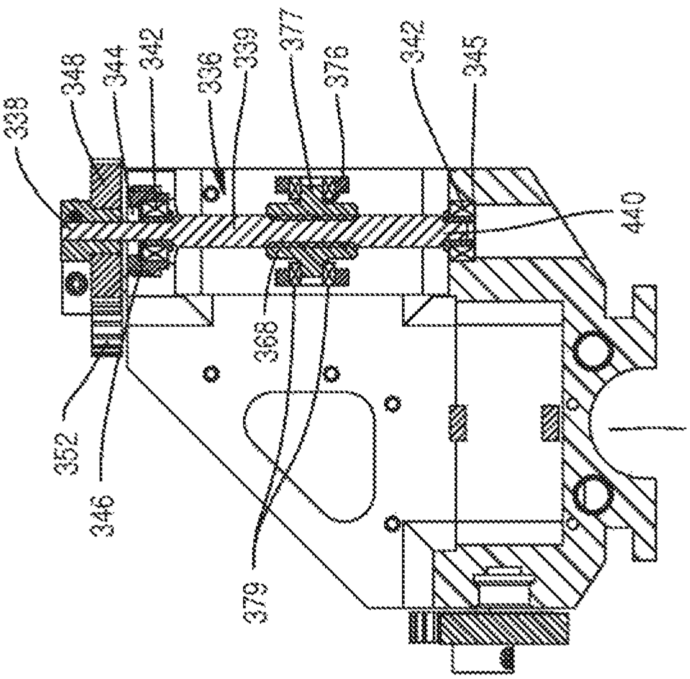

FIG. 17A

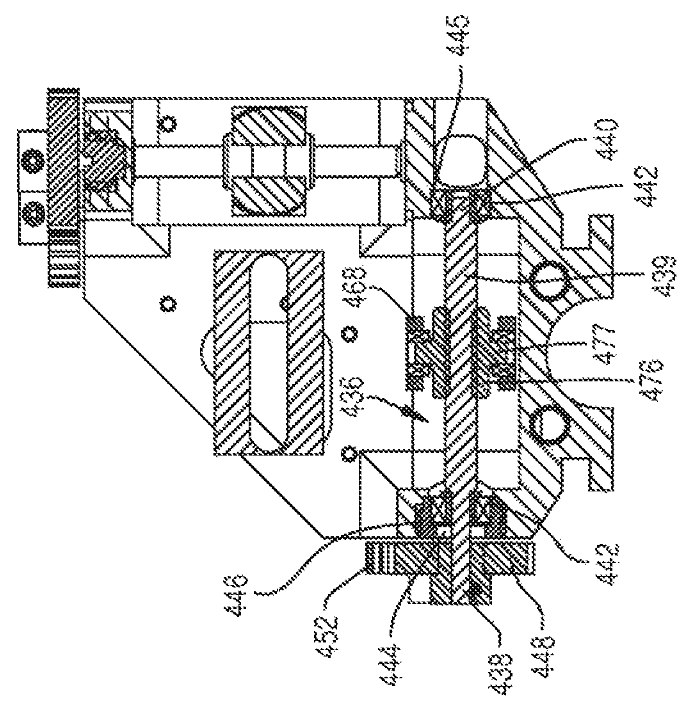

FIG. 17B

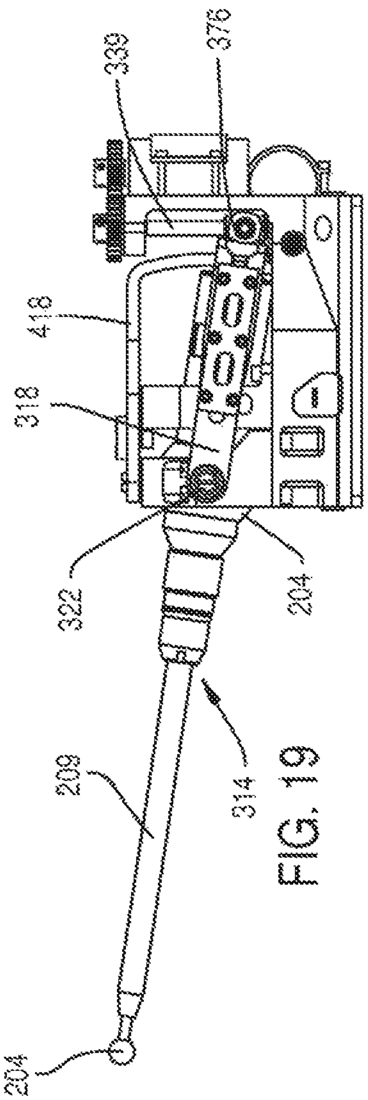

FIG. 19

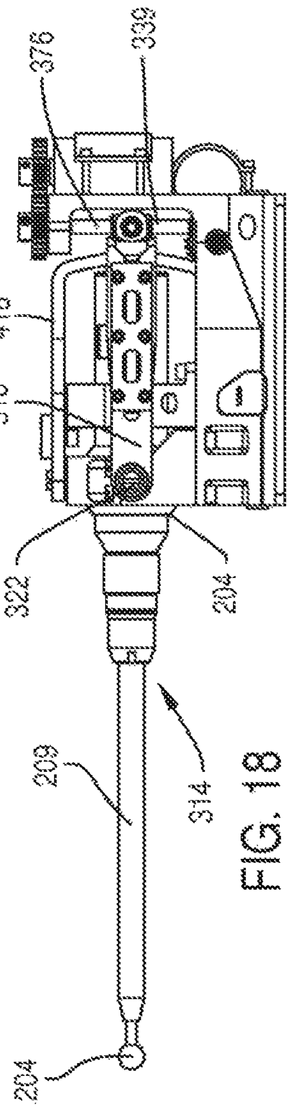

FIG. 18

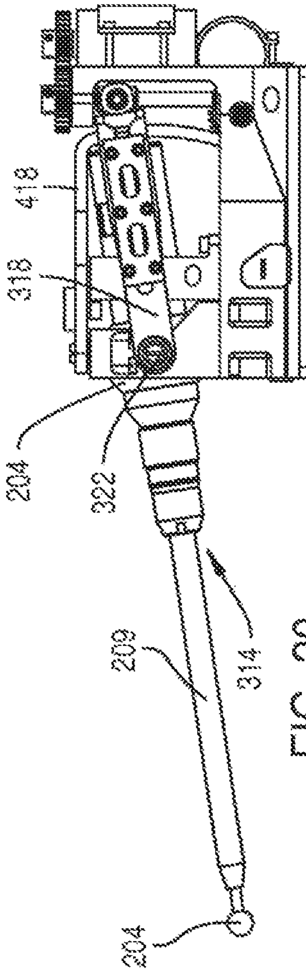

FIG. 20

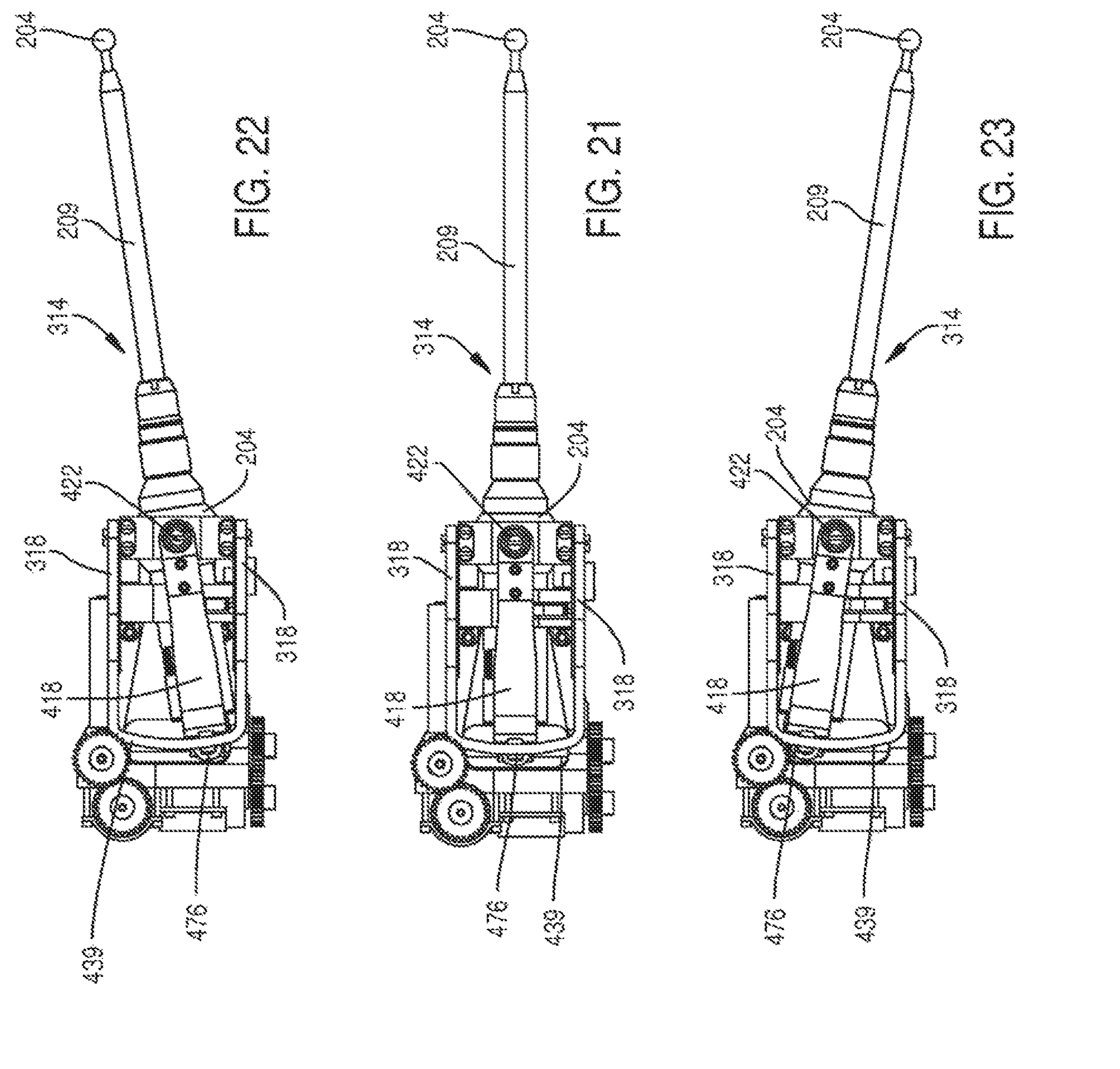

FIG. 22

FIG. 21

FIG. 23

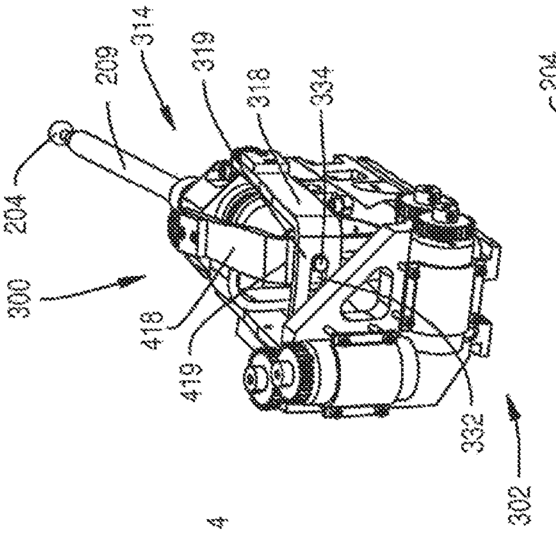

FIG. 26

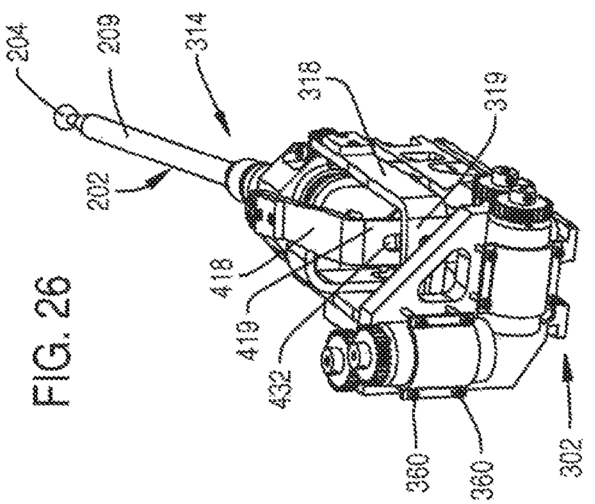

FIG. 27

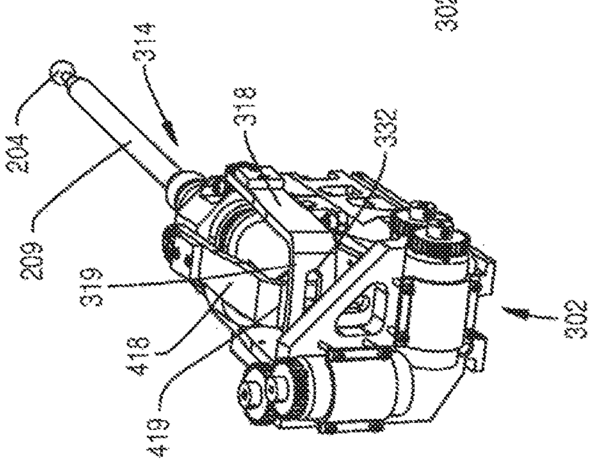

FIG. 25

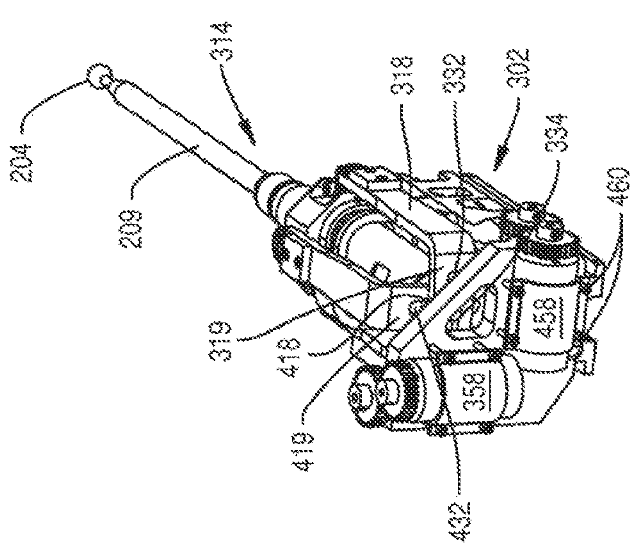

FIG. 24

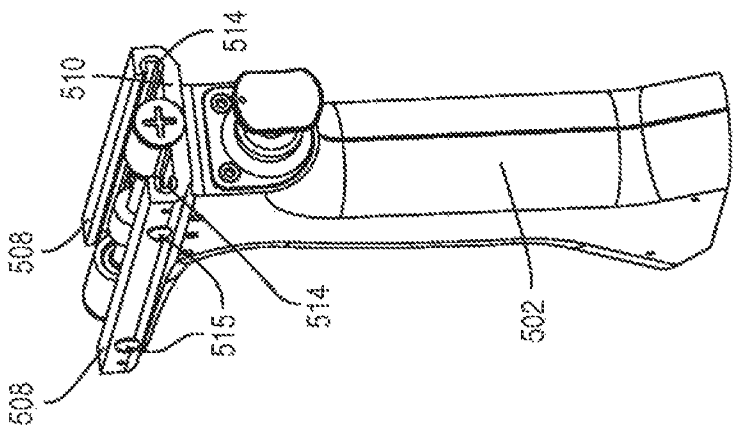

FIG. 29

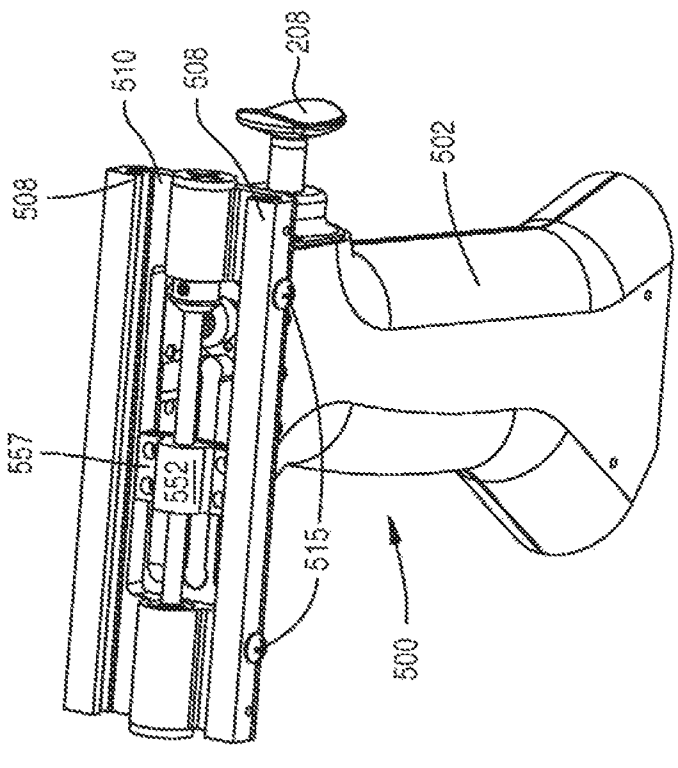

FIG. 28

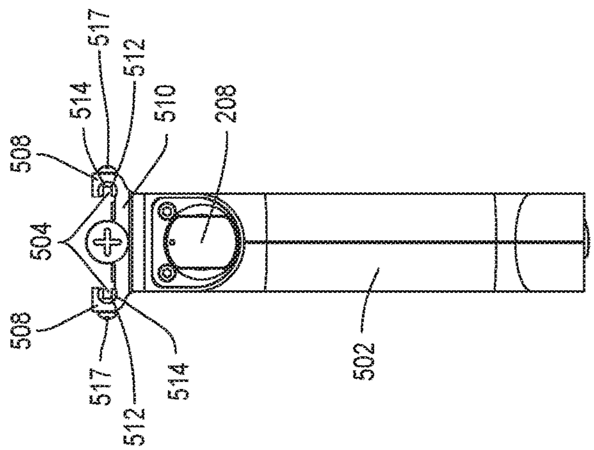

FIG. 34

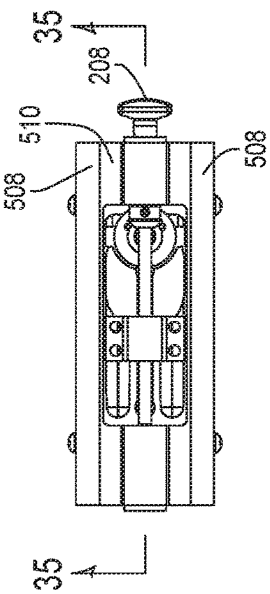

FIG. 31

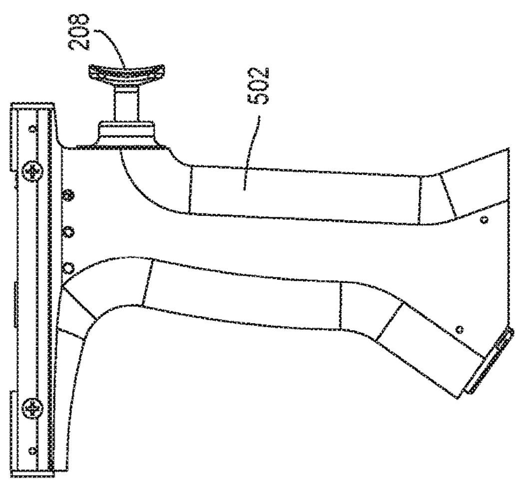

FIG. 30

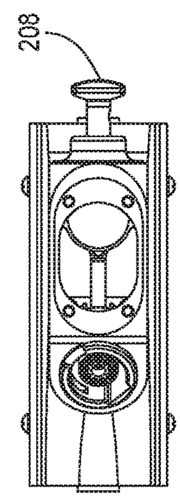

FIG. 32

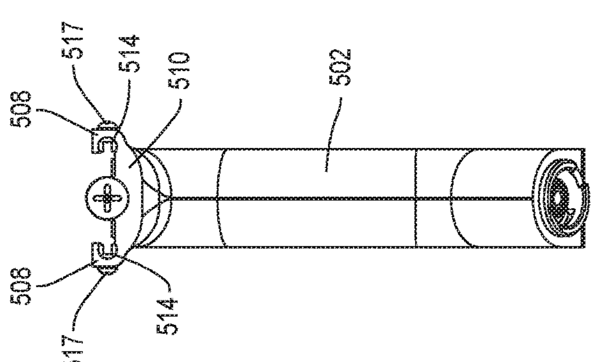

FIG. 33

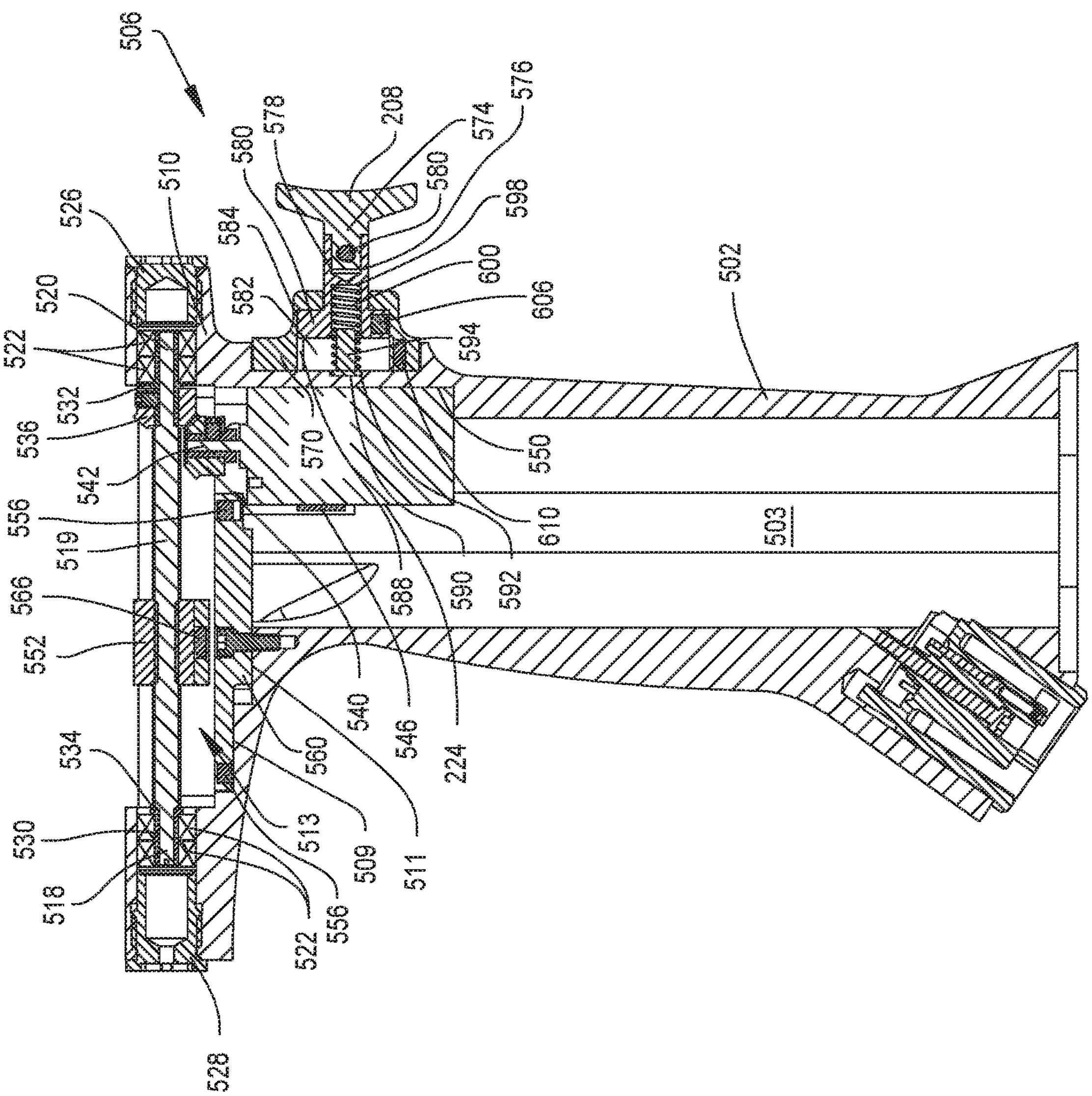
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FIG. 35

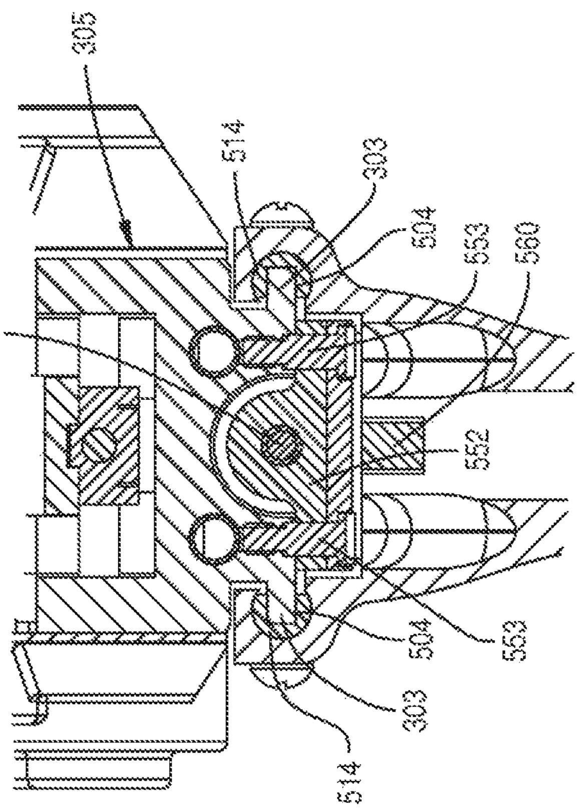

FIG. 35A

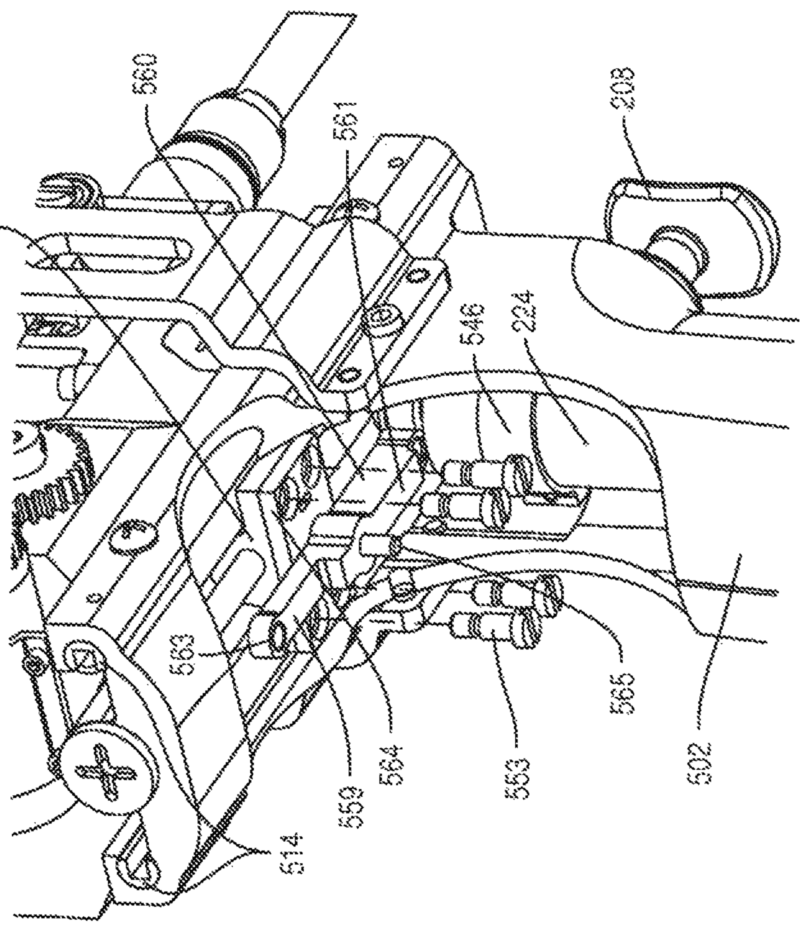

FIG. 35B

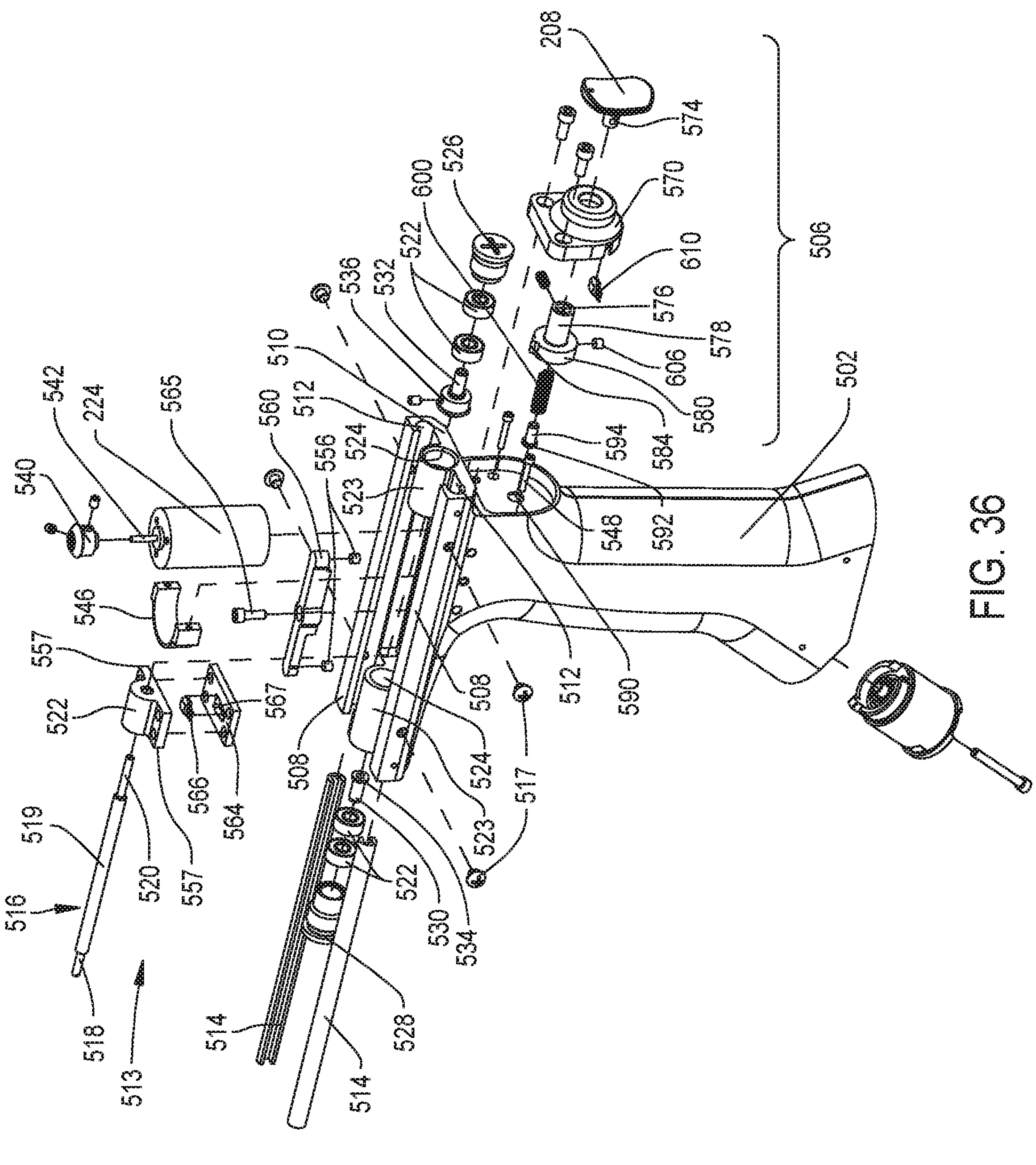
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FIG. 36

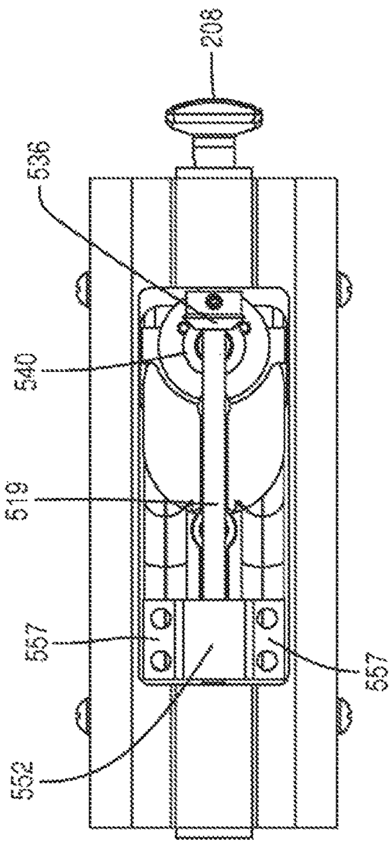

FIG. 38

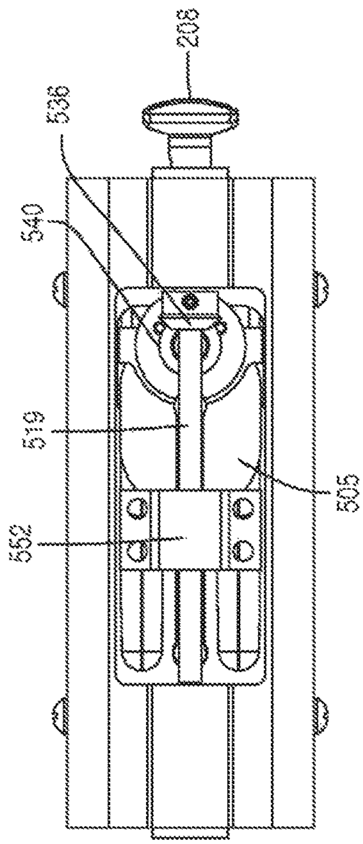

FIG. 37

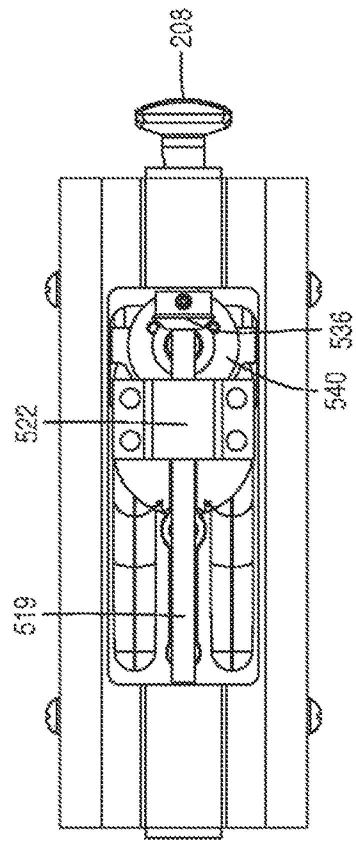

FIG. 39

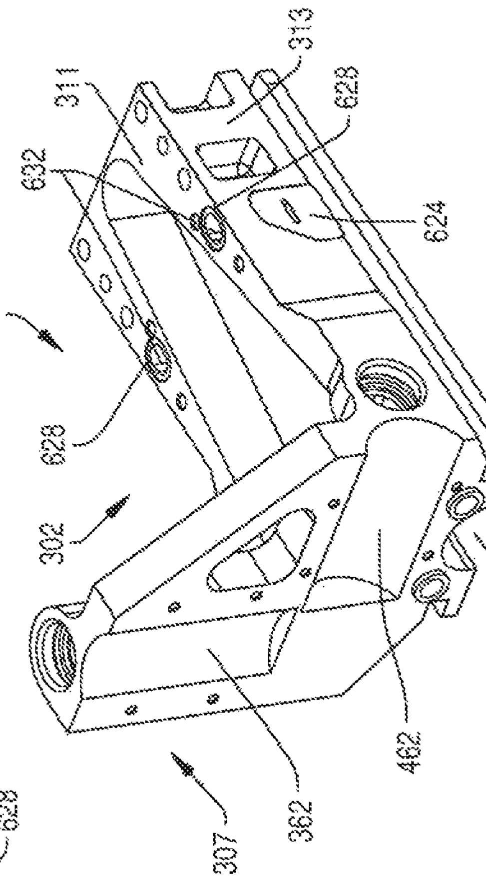
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FIG. 41

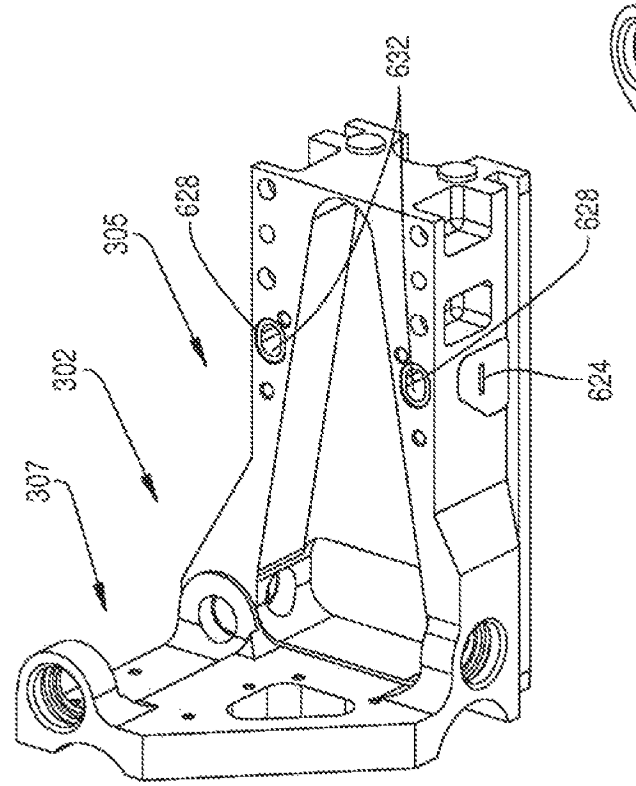
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FIG. 40

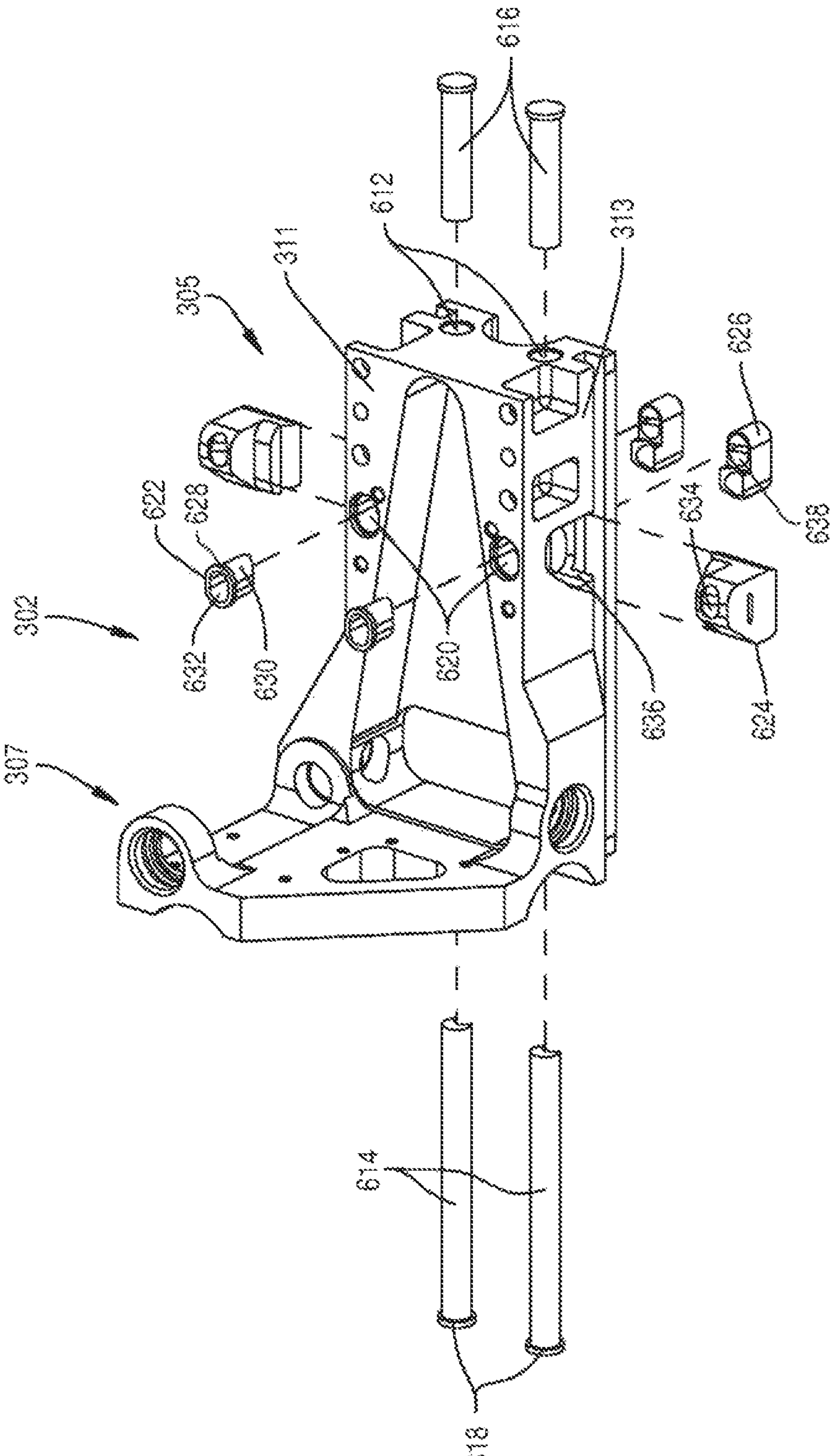
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FIG. 42

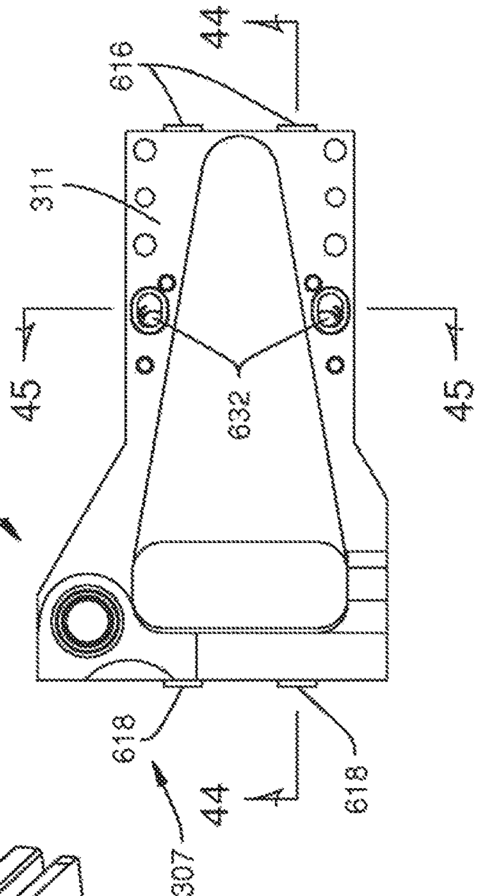


FIG. 43A

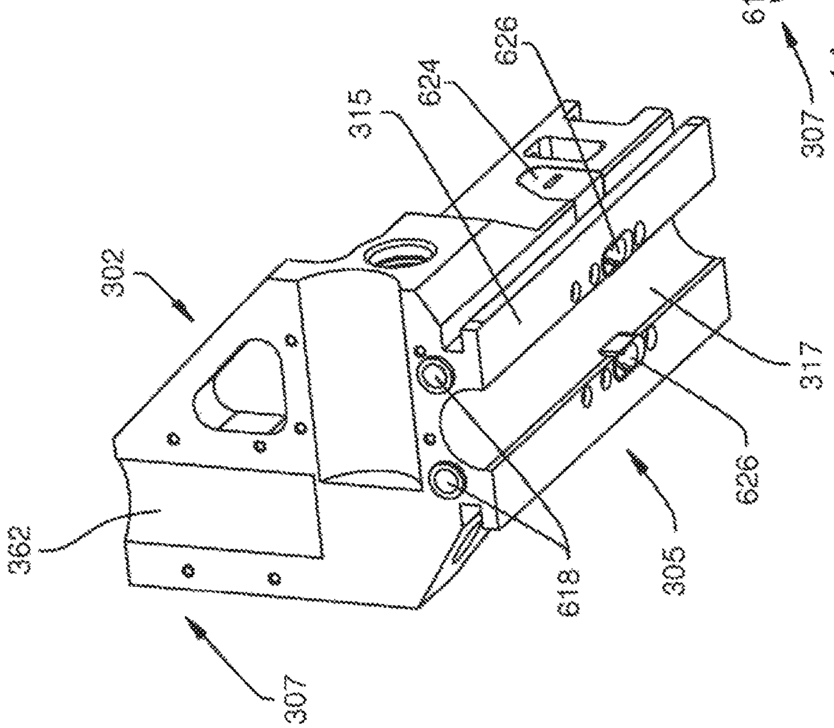


FIG. 43

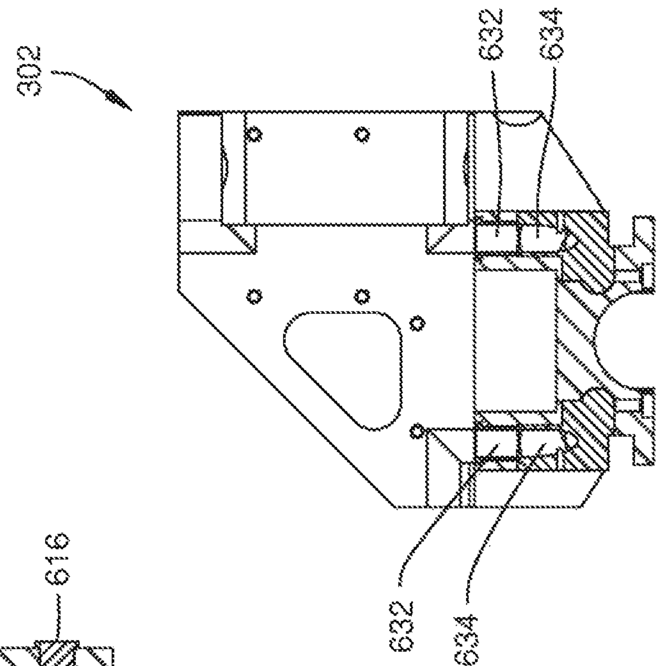


FIG. 45

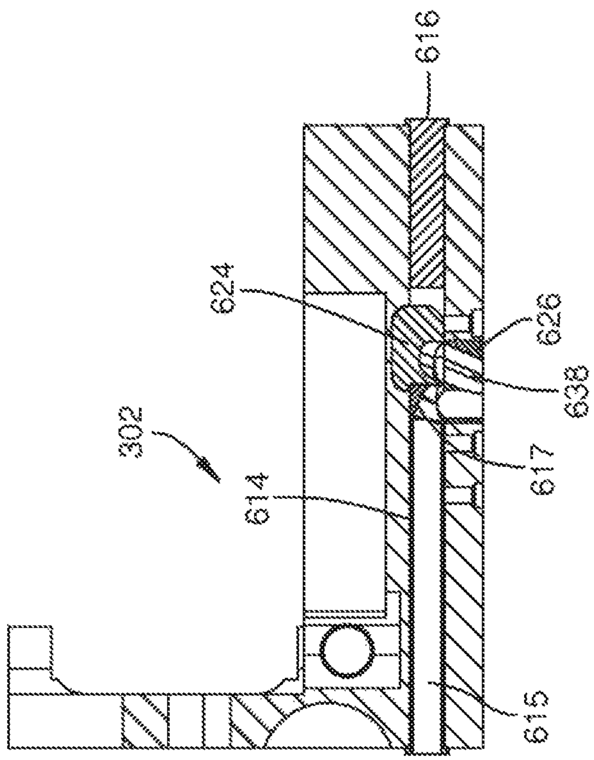


FIG. 44

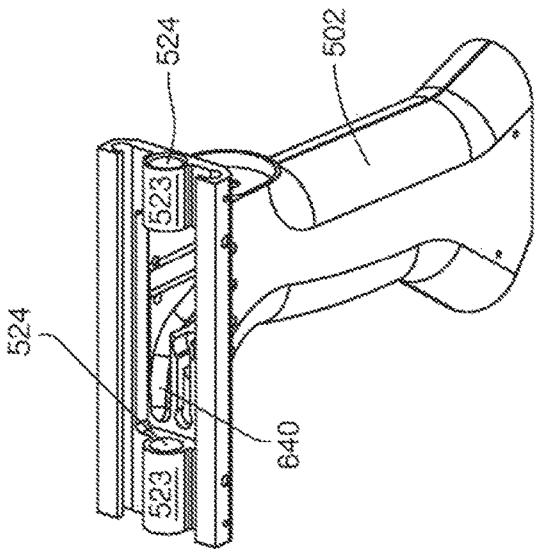


FIG. 46

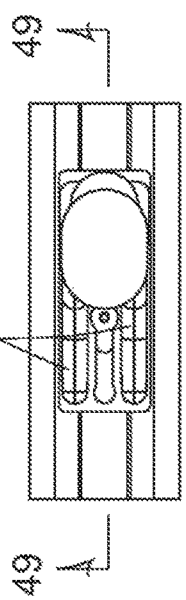


FIG. 47

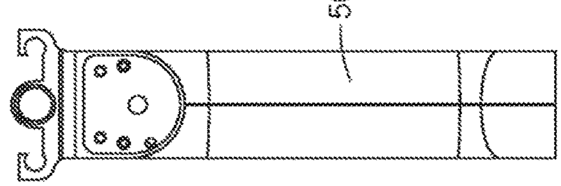


FIG. 48

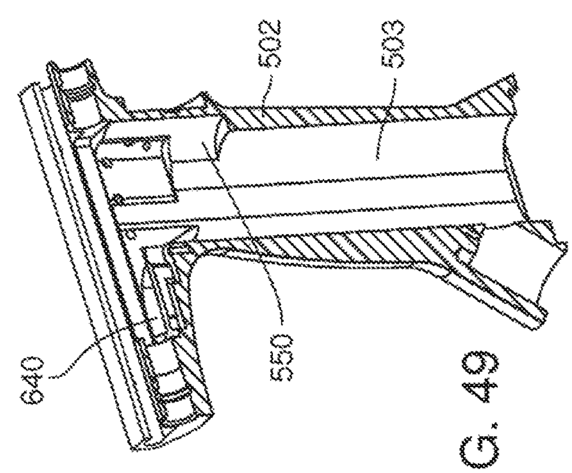


FIG. 49

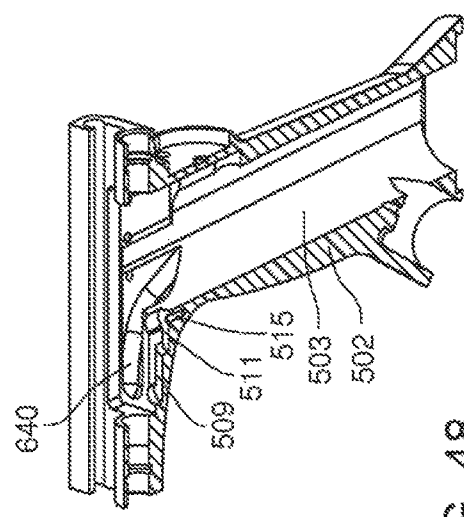


FIG. 50

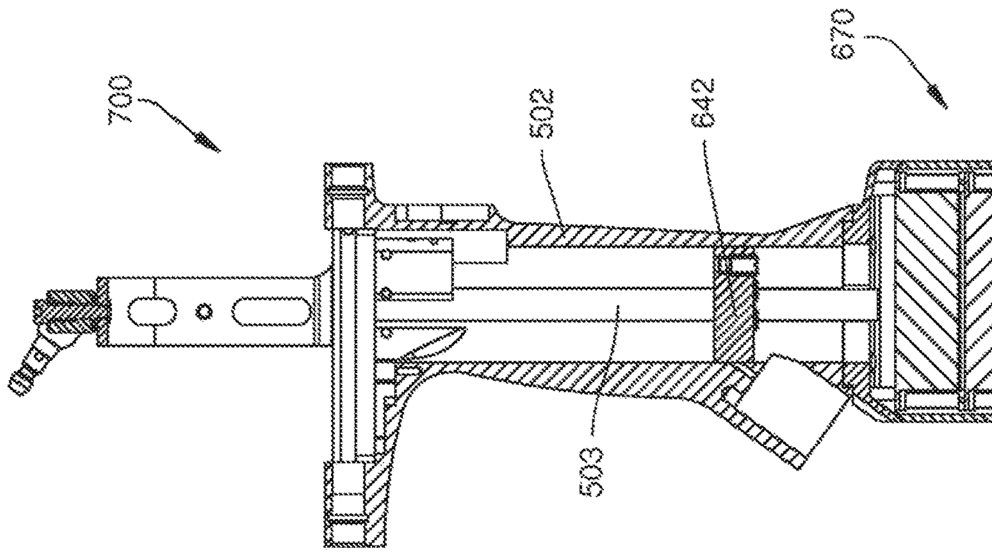


FIG. 52

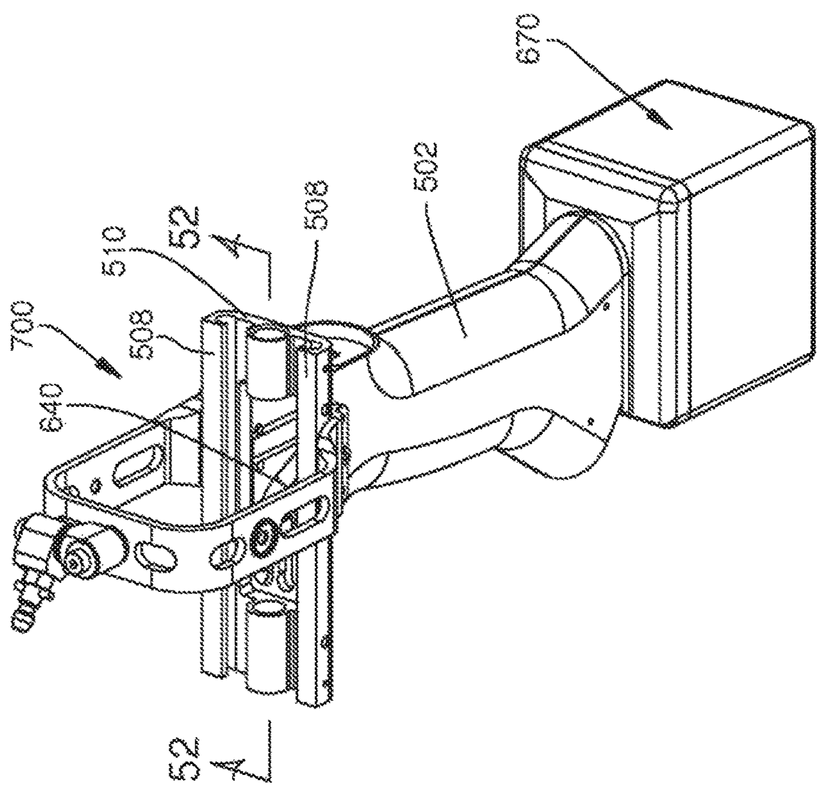


FIG. 51

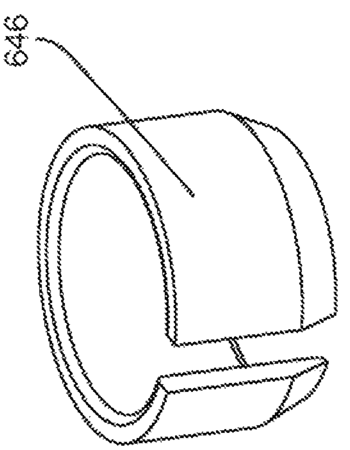


FIG. 53A

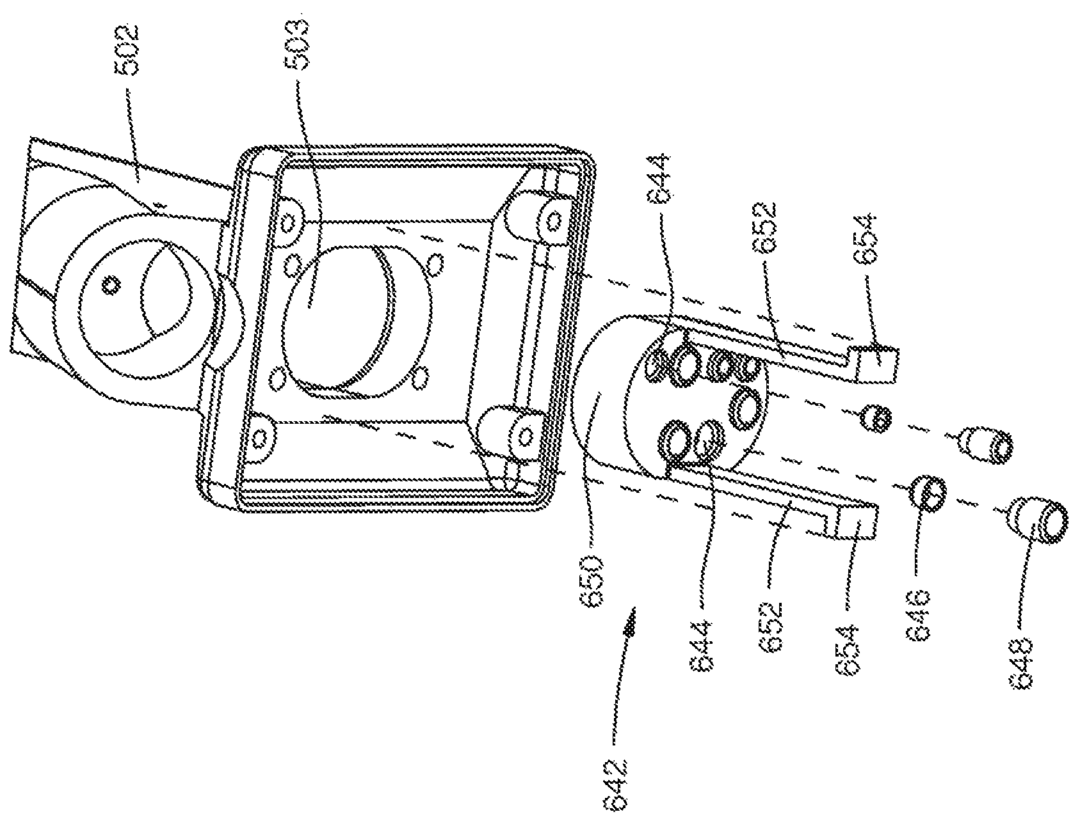


FIG. 53

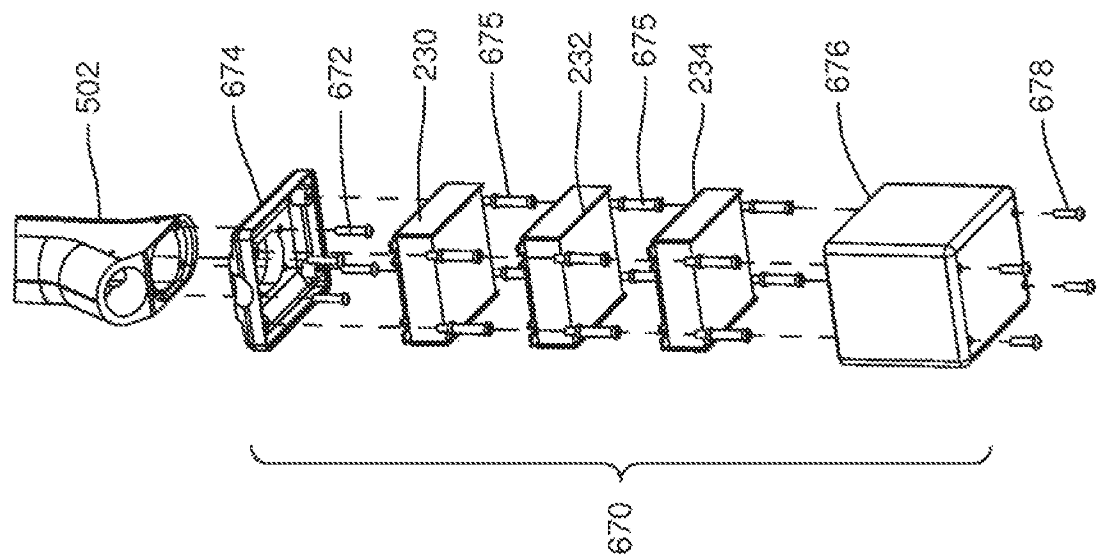
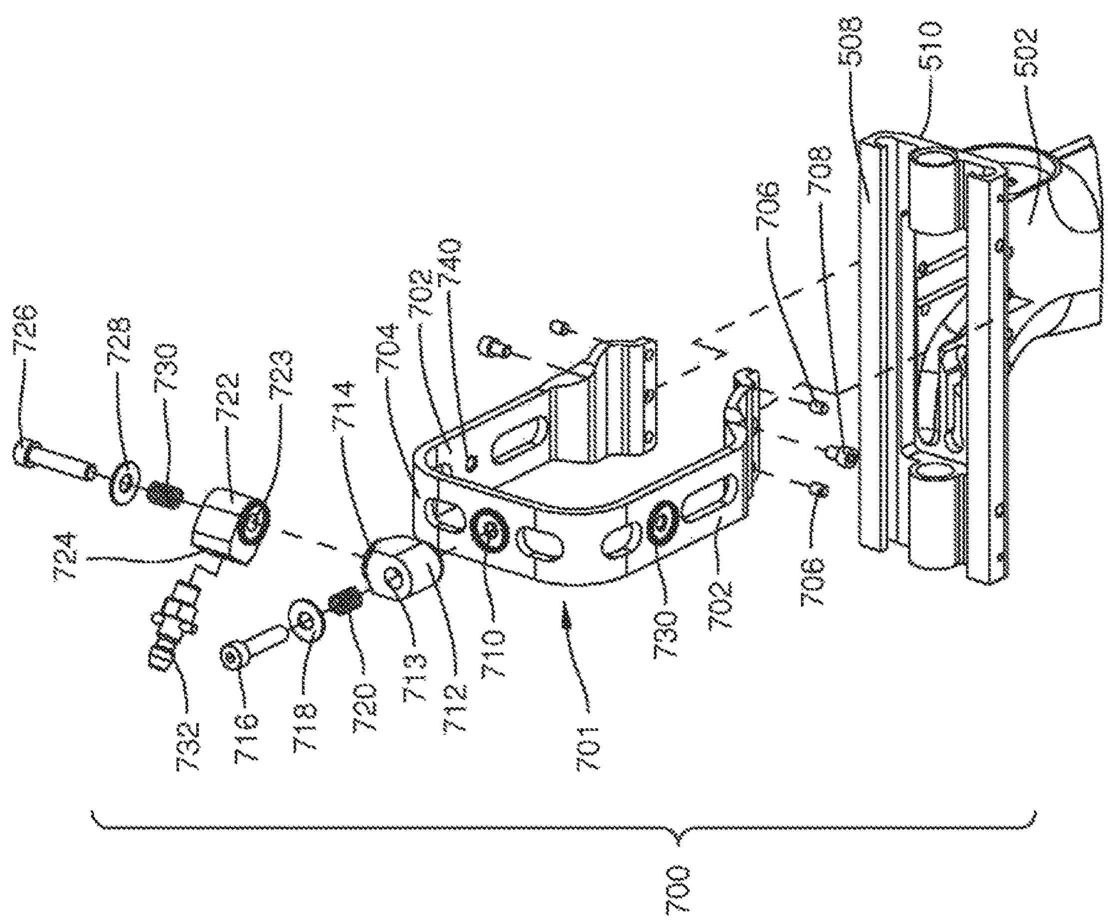


FIG. 54


726
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730
702
706
708
706
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510
502
700

FIG. 55

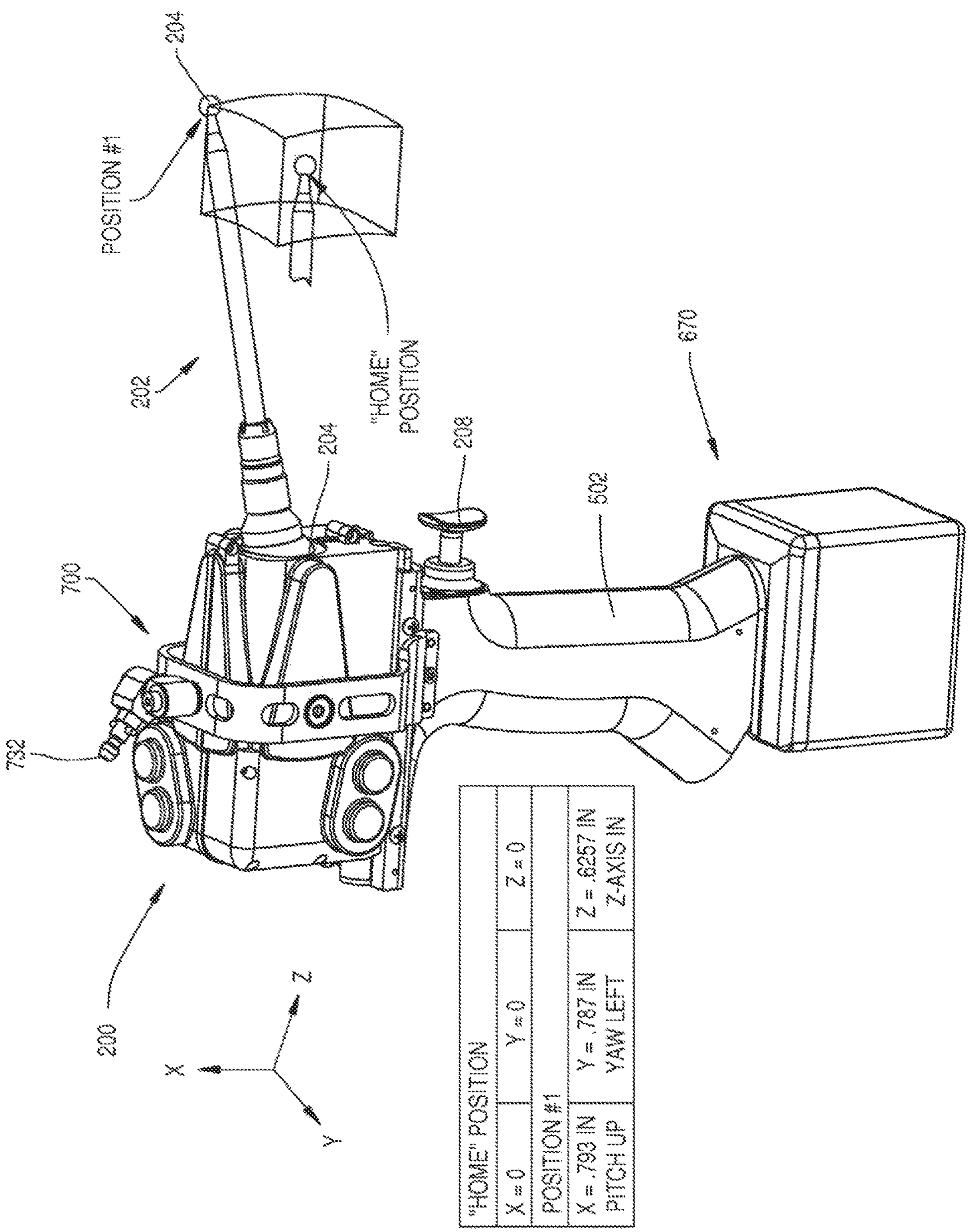

204
POSITION #1
"HOME" POSITION
202
204
208
670
502
700
732
200
X
Y
Z
"HOME" POSITION
X = 0
Y = 0
Z = 0
POSITION #1
X = .793 IN PITCH UP
Y = .787 IN YAW LEFT
Z = .6257 IN Z-AXIS IN

FIG. 56

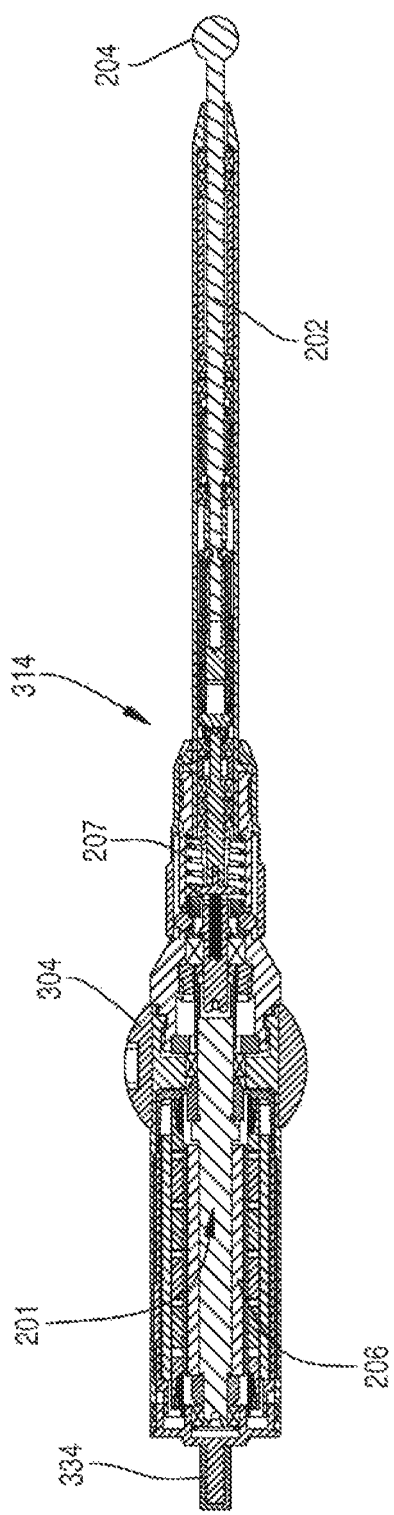


FIG. 57

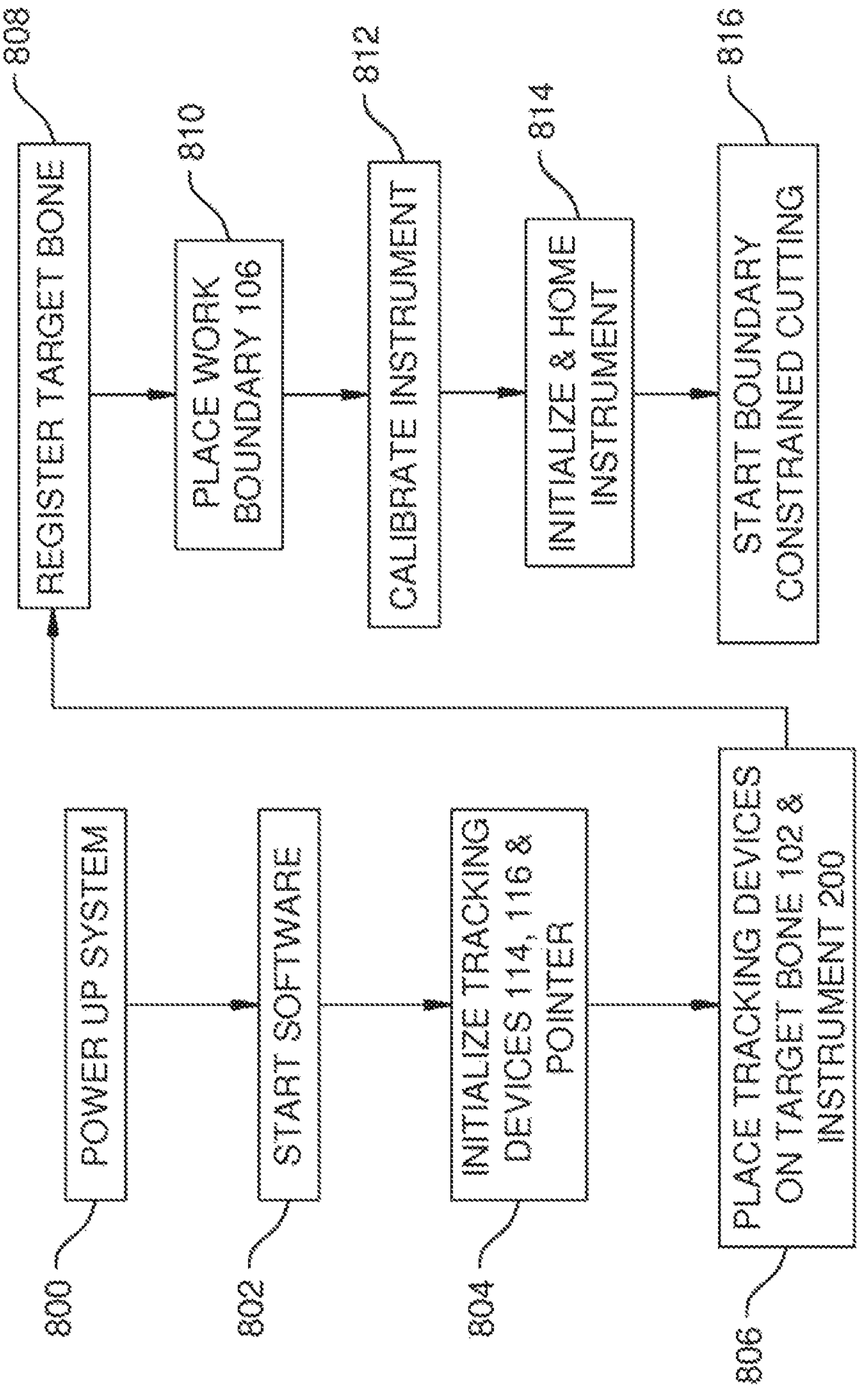

800
POWER UP SYSTEM
802
START SOFTWARE
804
INITIALIZE TRACKING DEVICES 114, 116 & POINTER
806
PLACE TRACKING DEVICES ON TARGET BONE 102 & INSTRUMENT 200
808
REGISTER TARGET BONE
810
PLACE WORK BOUNDARY 106
812
CALIBRATE INSTRUMENT
814
INITIALIZE & HOME INSTRUMENT
816
START BOUNDARY CONSTRAINED CUTTING

FIG. 58

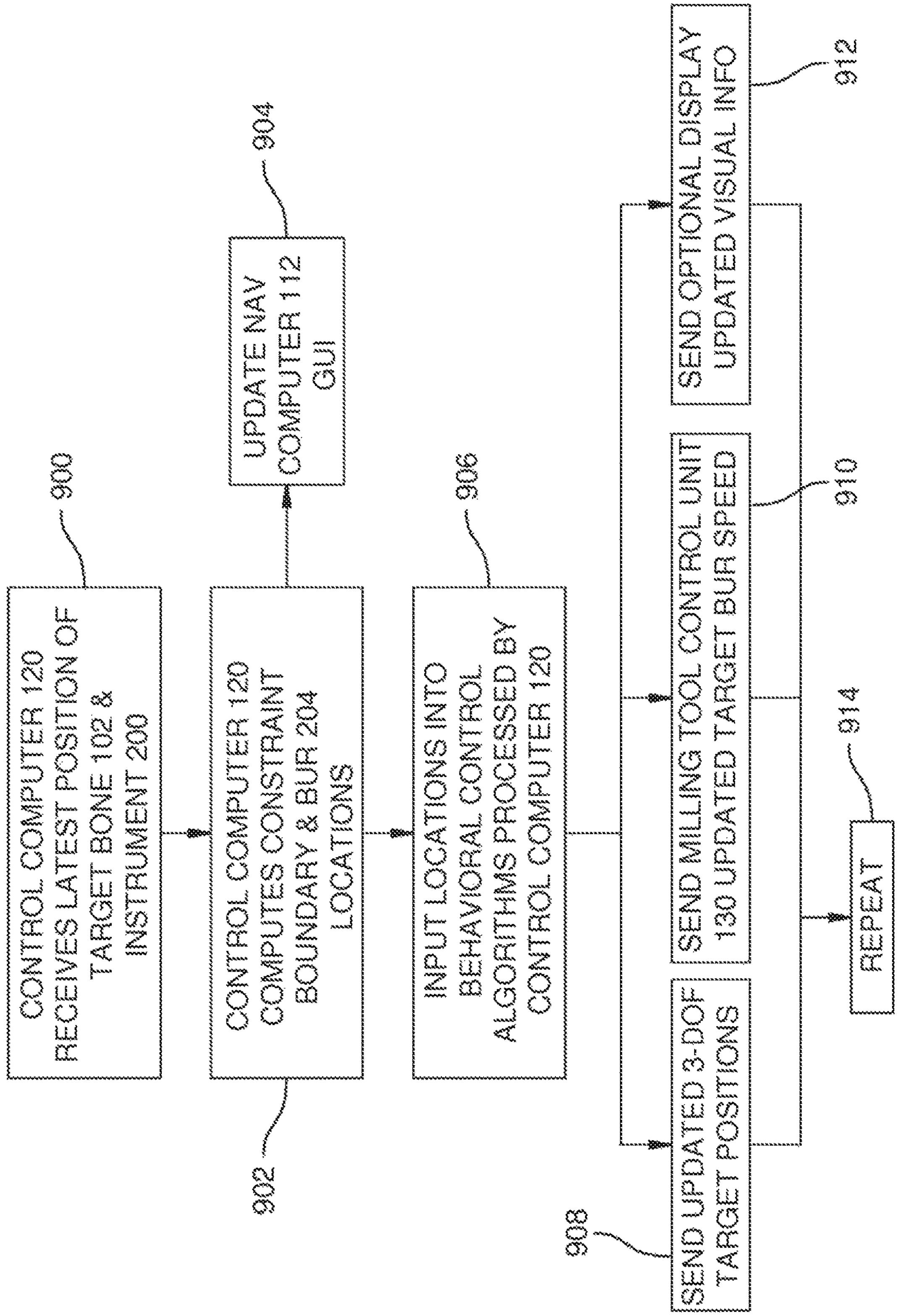

CONTROL COMPUTER 120 RECEIVES LATEST POSITION OF TARGET BONE 102 & INSTRUMENT 200
900
CONTROL COMPUTER 120 COMPUTES CONSTRAINT BOUNDARY & BUR 204 LOCATIONS
902
UPDATE NAV COMPUTER 112 GUI
904
INPUT LOCATIONS INTO BEHAVIORAL CONTROL ALGORITHMS PROCESSED BY CONTROL COMPUTER 120
906
SEND UPDATED 3-DOF TARGET POSITIONS
908
SEND MILLING TOOL CONTROL UNIT 130 UPDATED TARGET BUR SPEED
910
SEND OPTIONAL DISPLAY UPDATED VISUAL INFO
912
REPEAT
914

FIG. 59

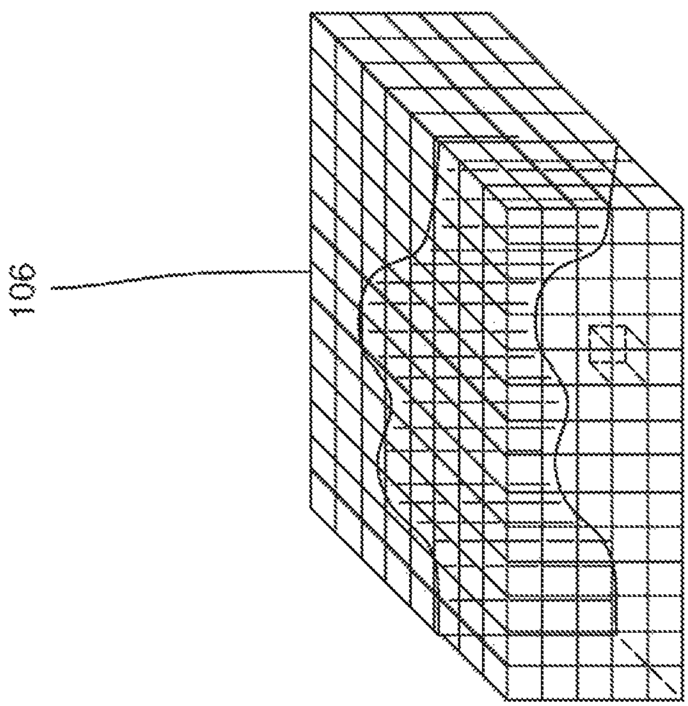


FIG. 61

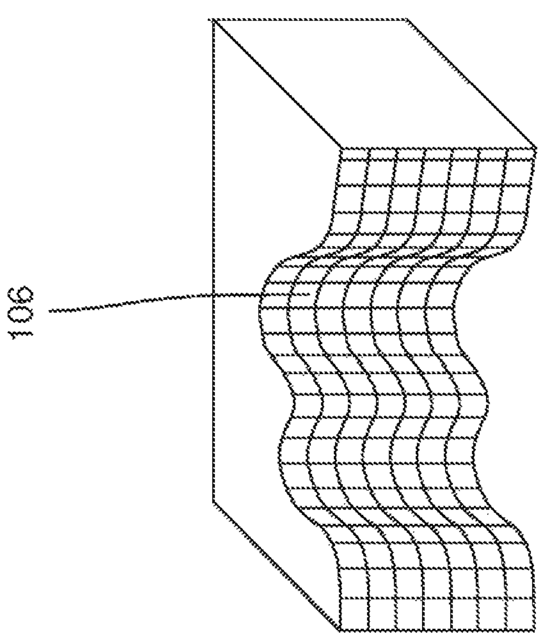


FIG. 60

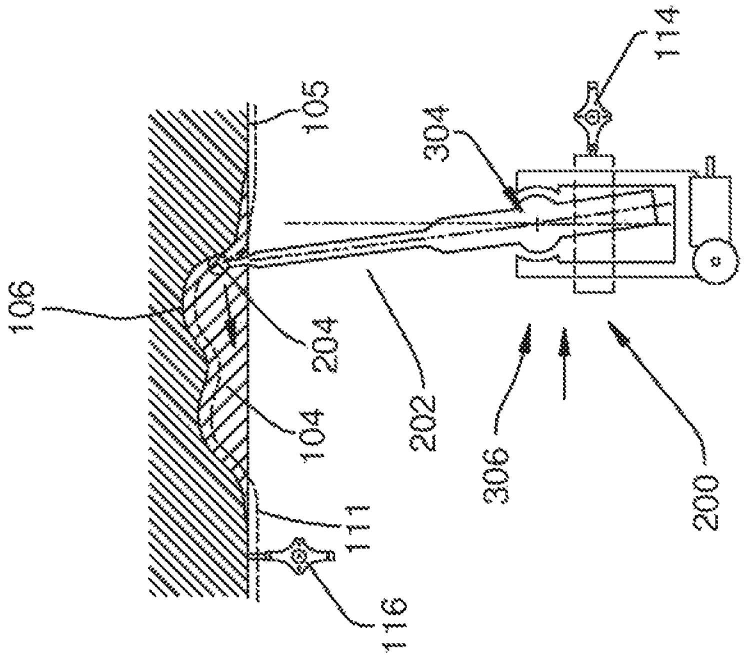

114
105
304
106
204
202
104
306
200
111
116

FIG. 63

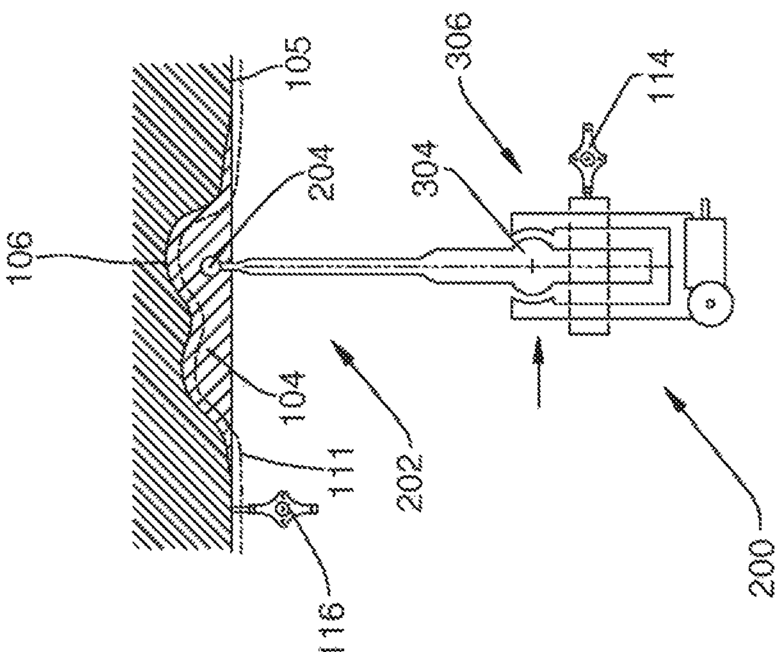

306
105
114
204
304
106
104
202
111
200
116

FIG. 62

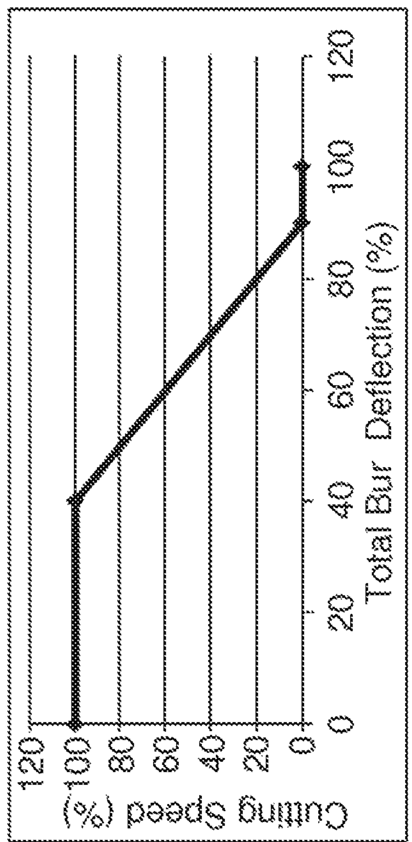


FIG. 64

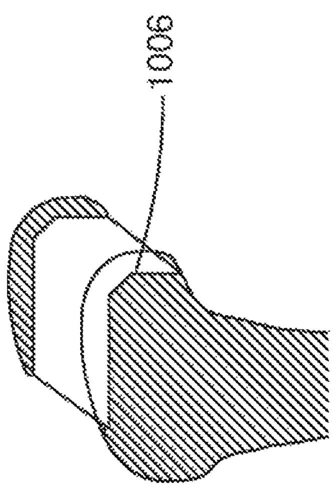


FIG. 65

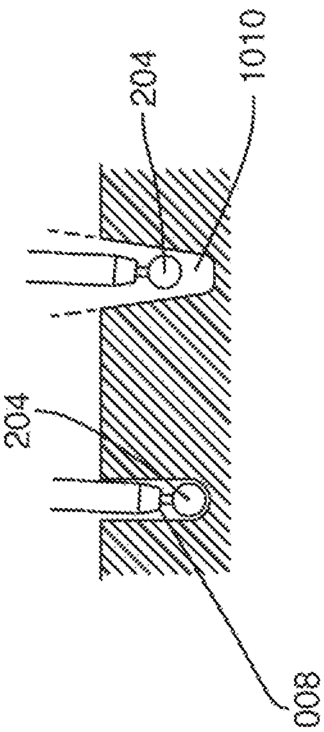


FIG. 66

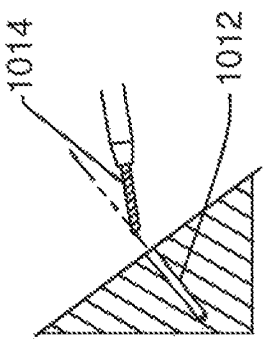


FIG. 67B

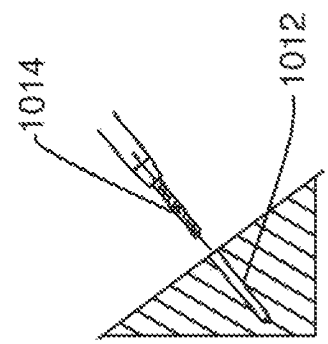


FIG. 67C

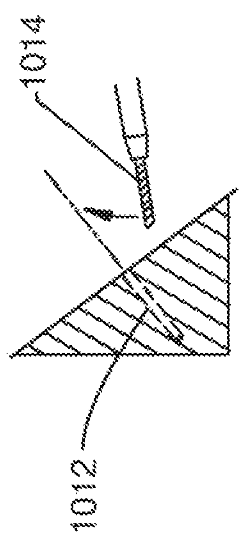


FIG. 67A

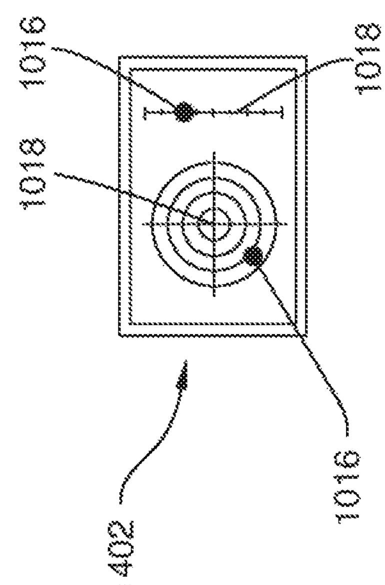


FIG. 68

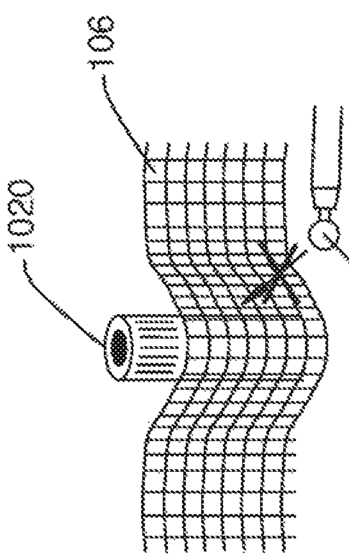


FIG. 69

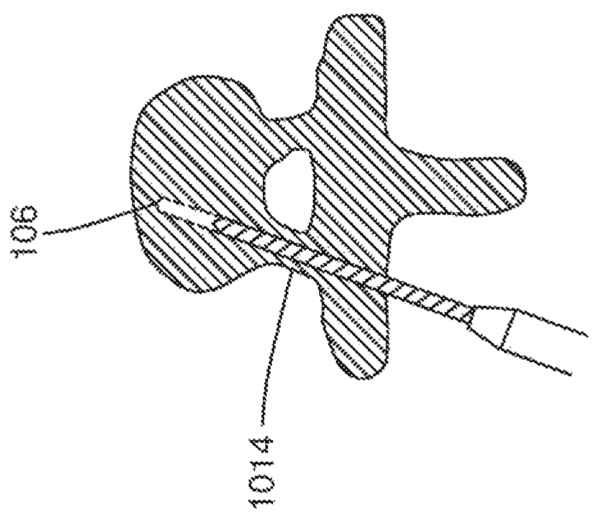


FIG. 70

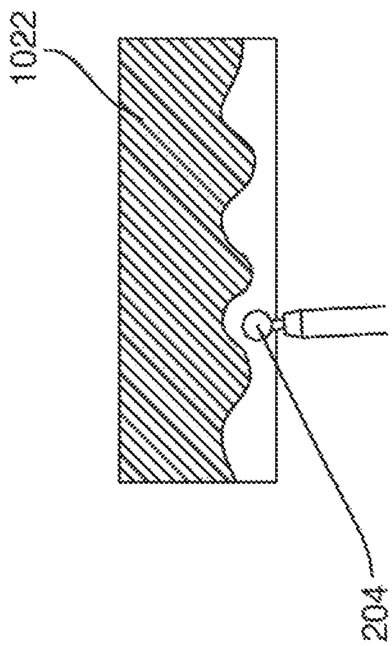


FIG. 71

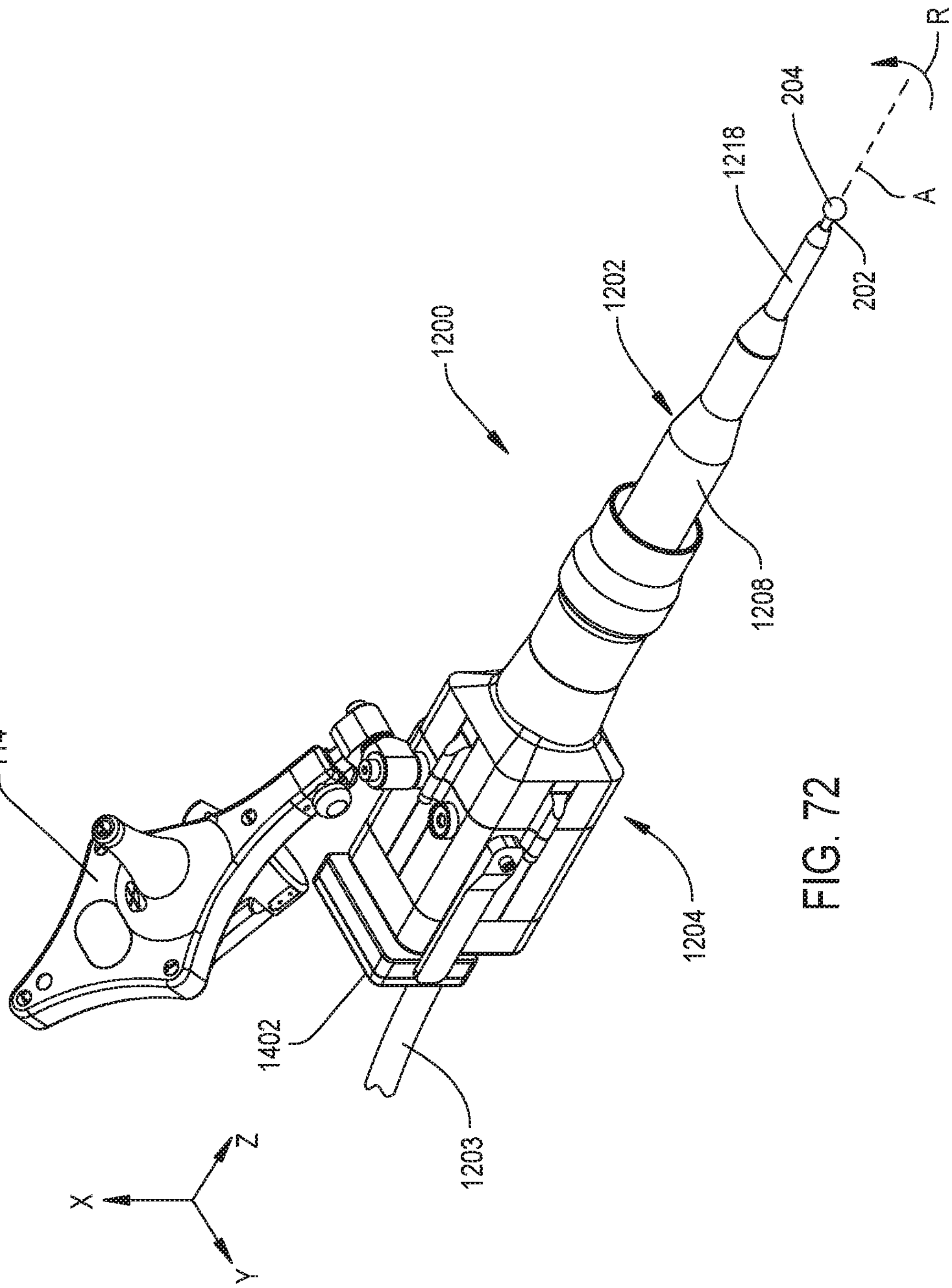


FIG. 72

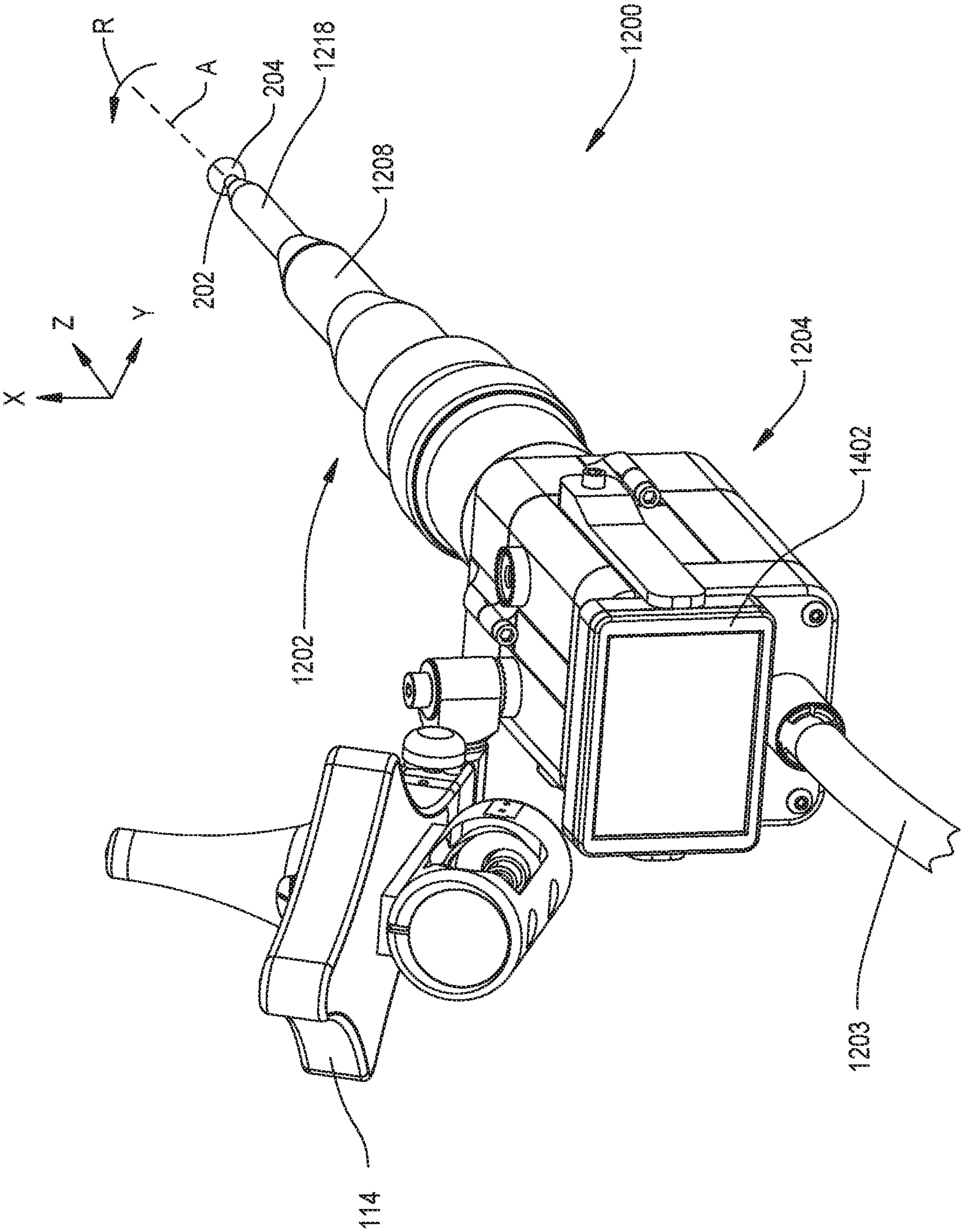
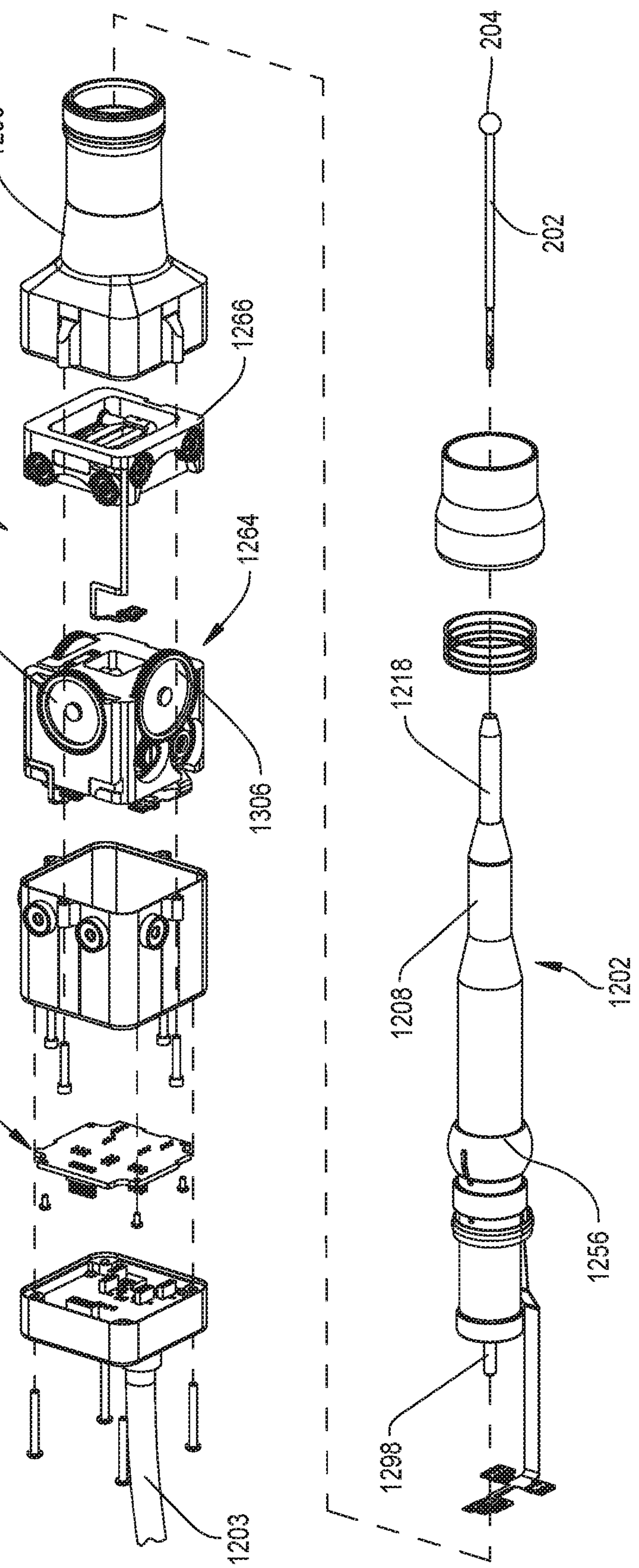


FIG. 73


1206
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1204
1264
1308
1306
1263
1203
204
202
1218
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1202
1256
1298

FIG. 74

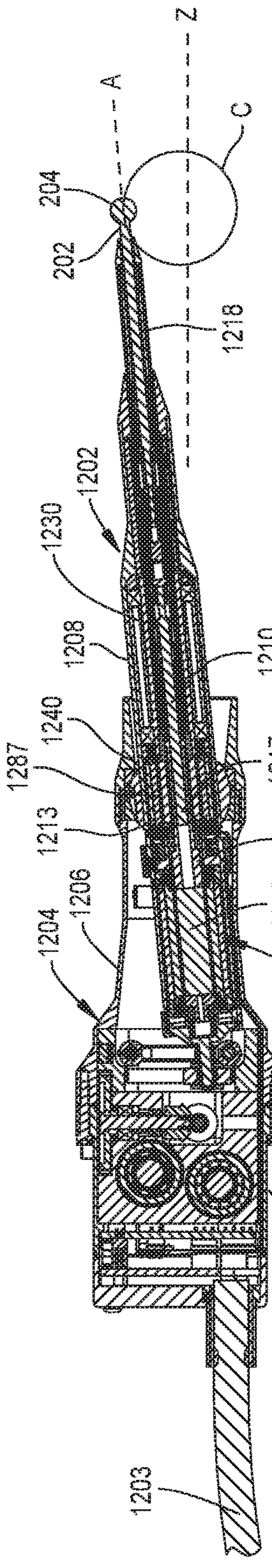


FIG. 75A

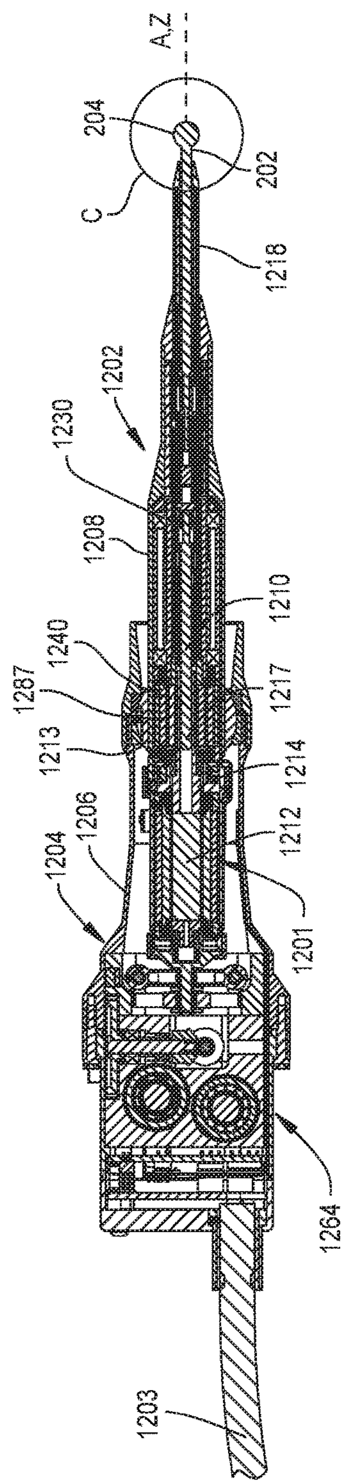


FIG. 75B

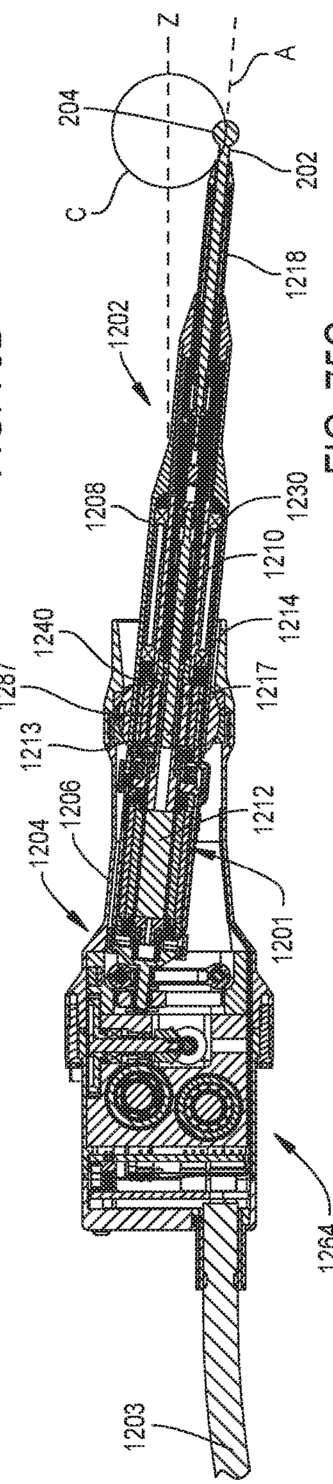
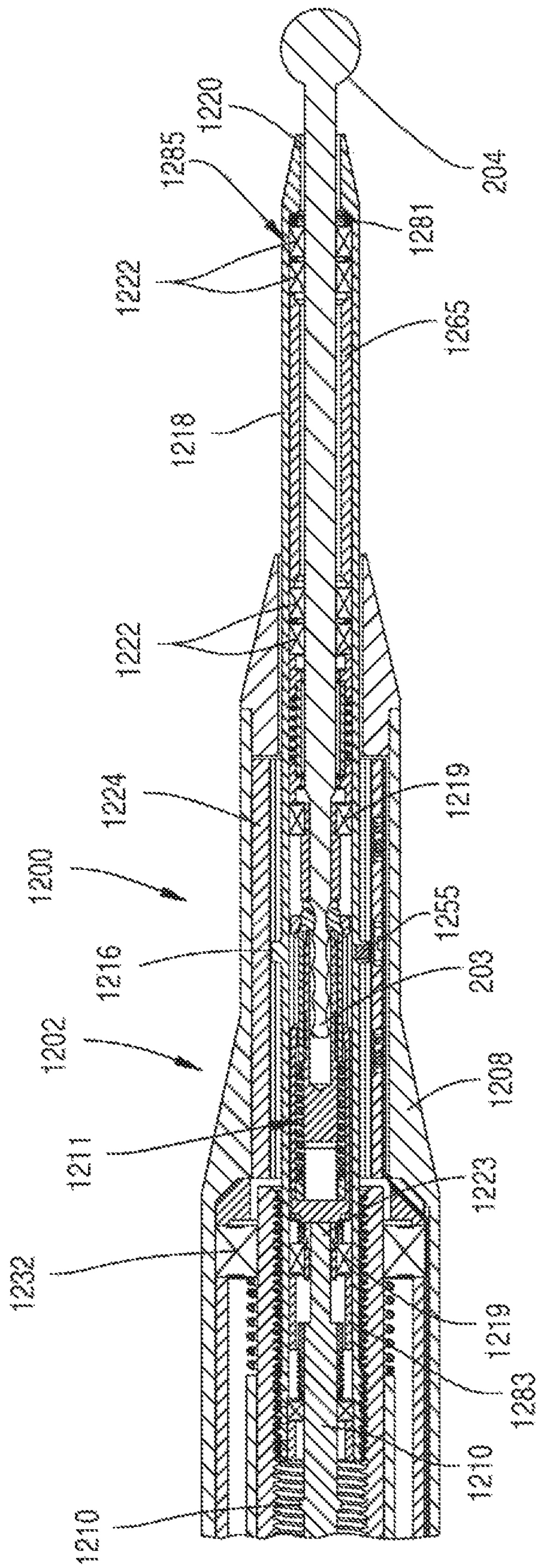


FIG. 75C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1222
1265
1218
1222
1224
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1200
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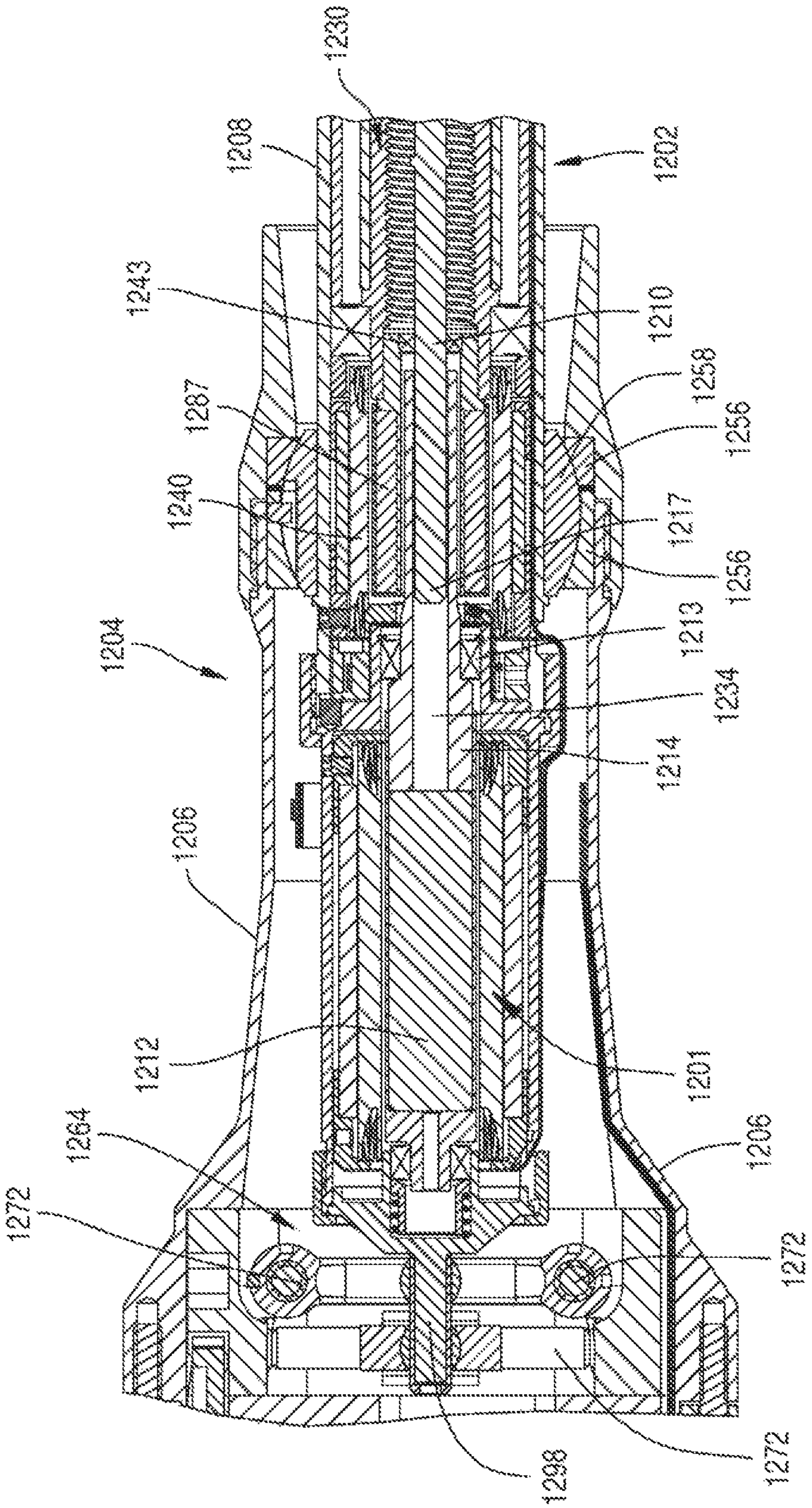
1216
203
1202
1208
1211
1223
1232
1219
1283
1210
1210

FIG. 76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1217
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1204
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1234
1214
1206
1212
1201
1264
1206
1272
1272
1298
1272

FIG. 77

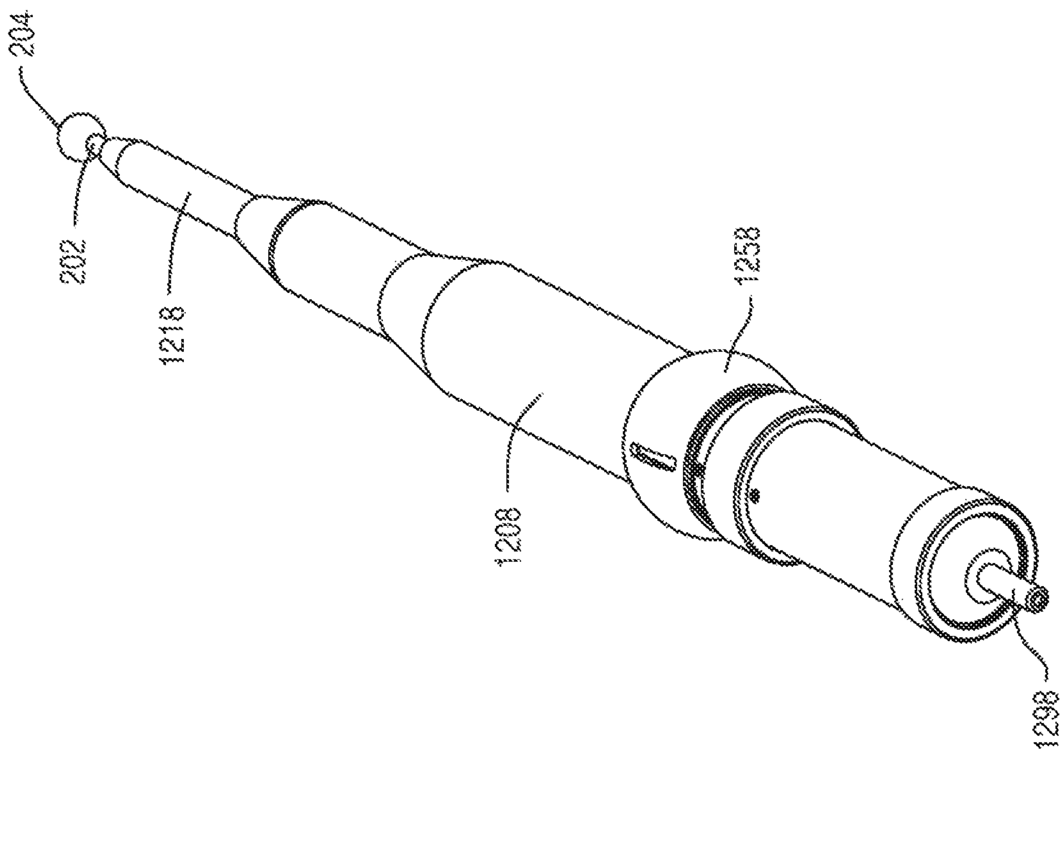
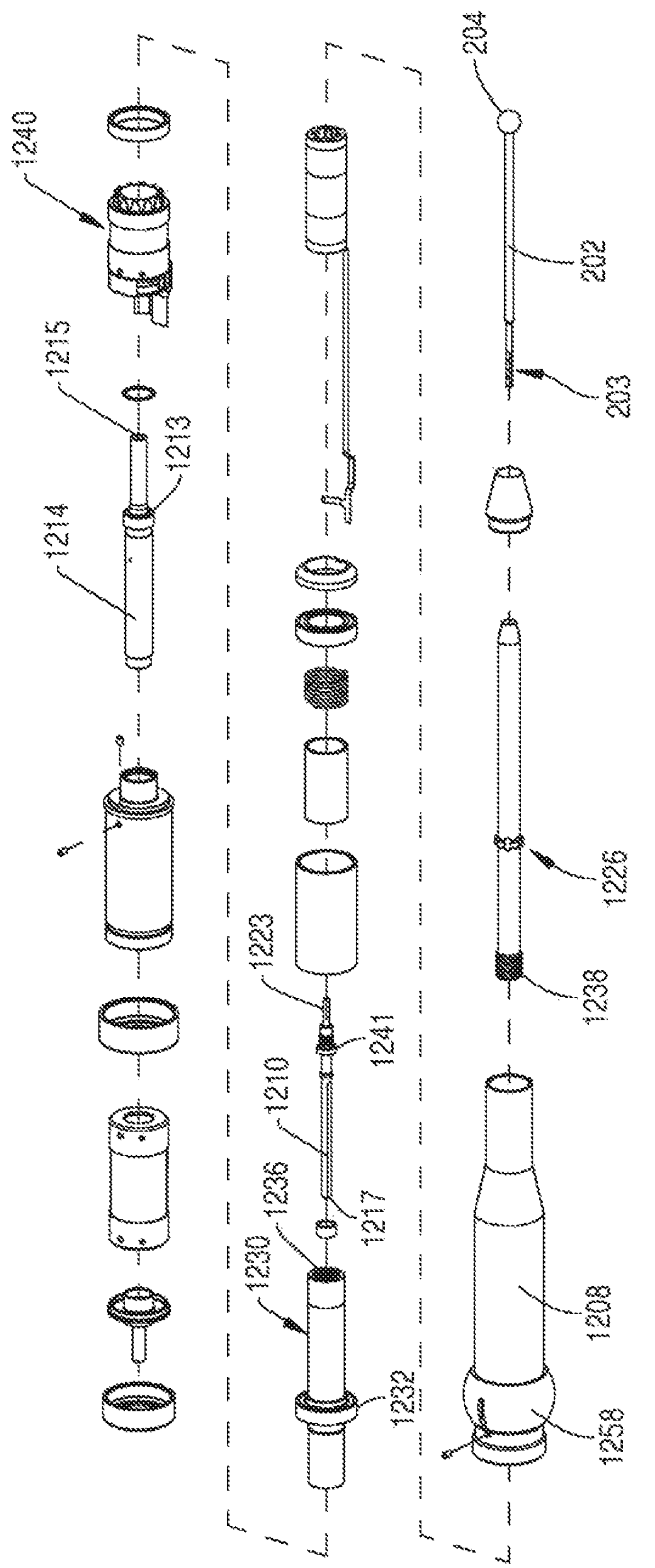


FIG. 78


1240
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1213
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1241
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1236
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1230
1232
204
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203
1226
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1208
1258

FIG. 79

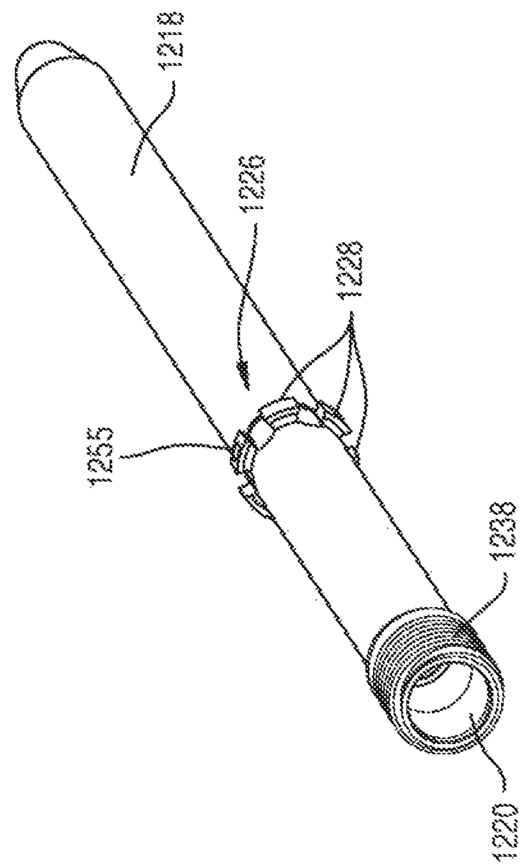
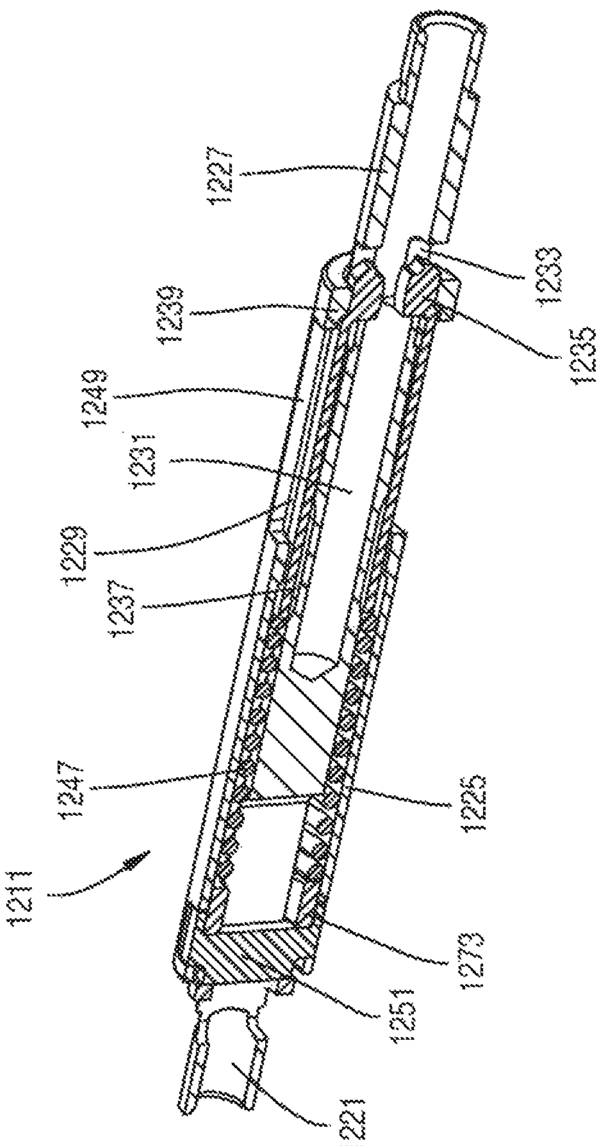


FIG. 80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1249
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1225
1211
1273
1251
1221

FIG. 81

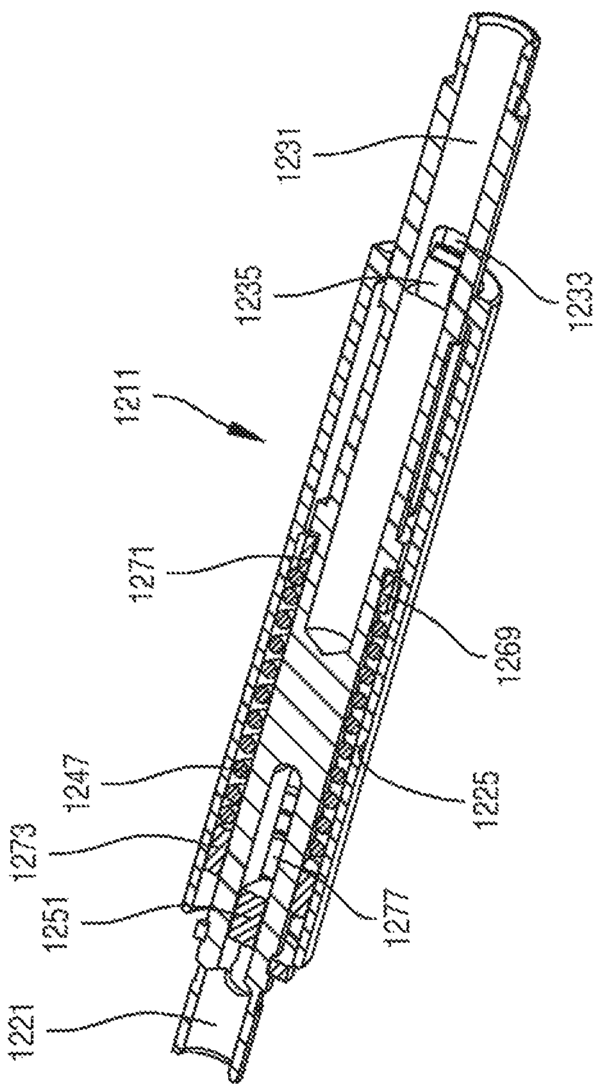
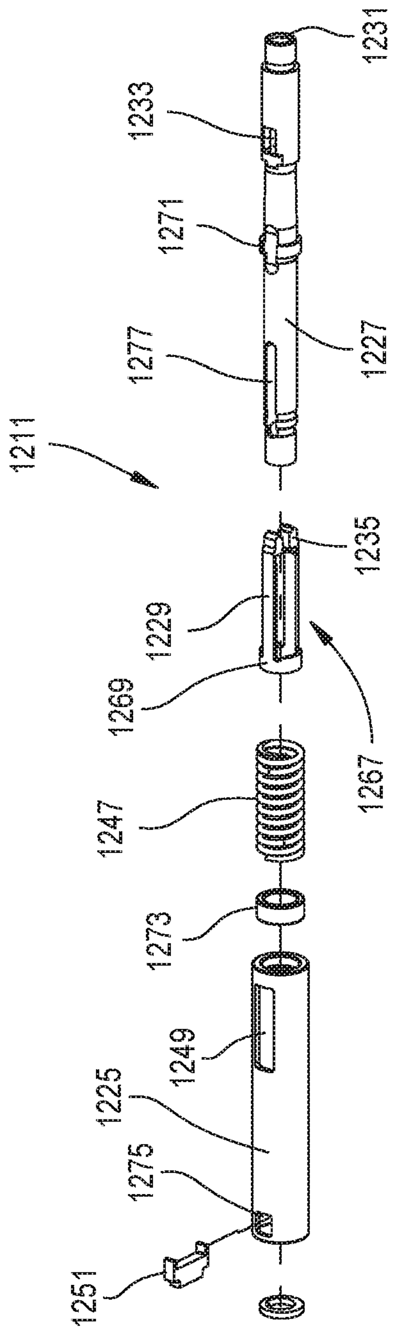


FIG. 82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1251

FIG. 83

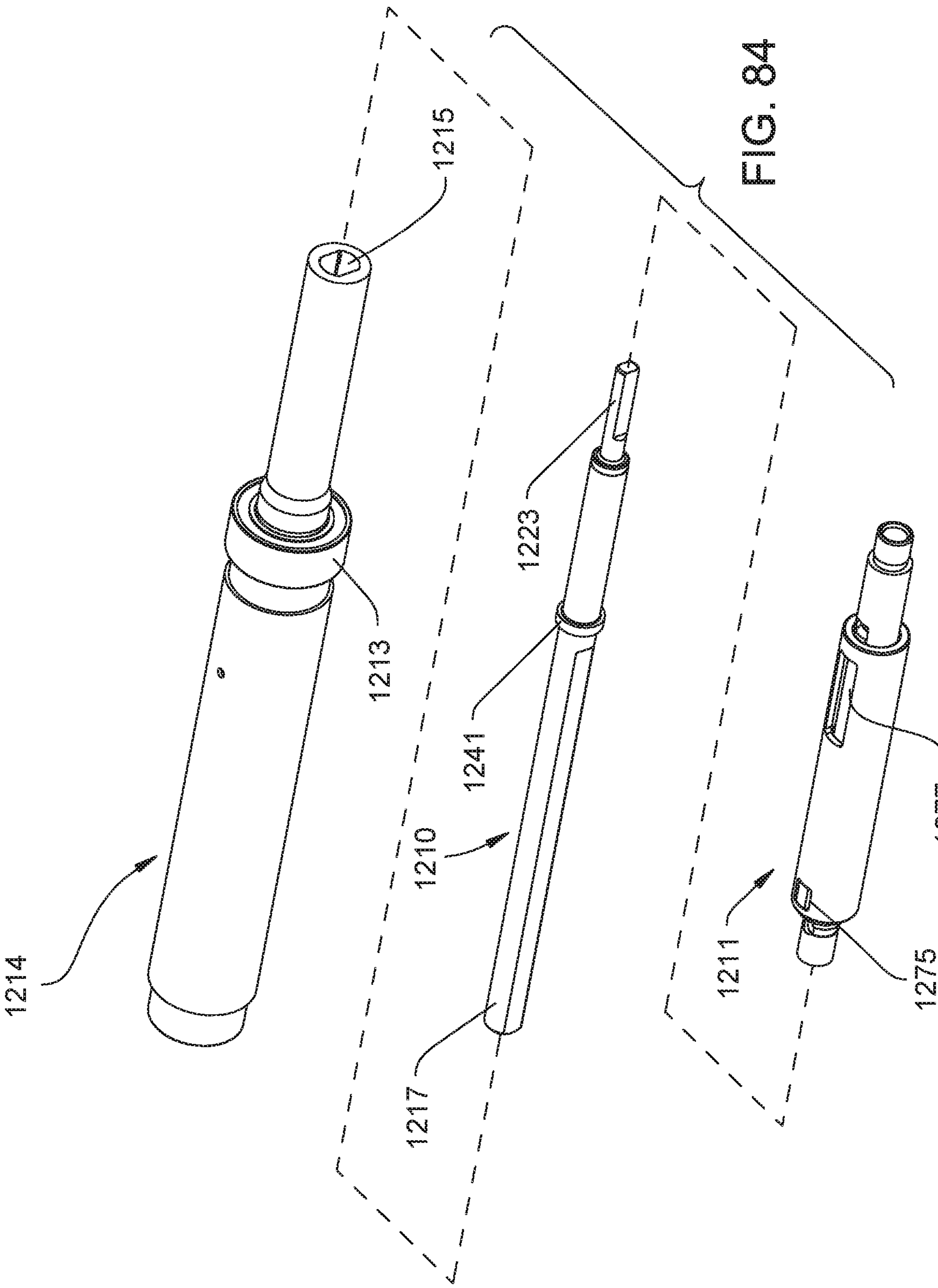


FIG. 84

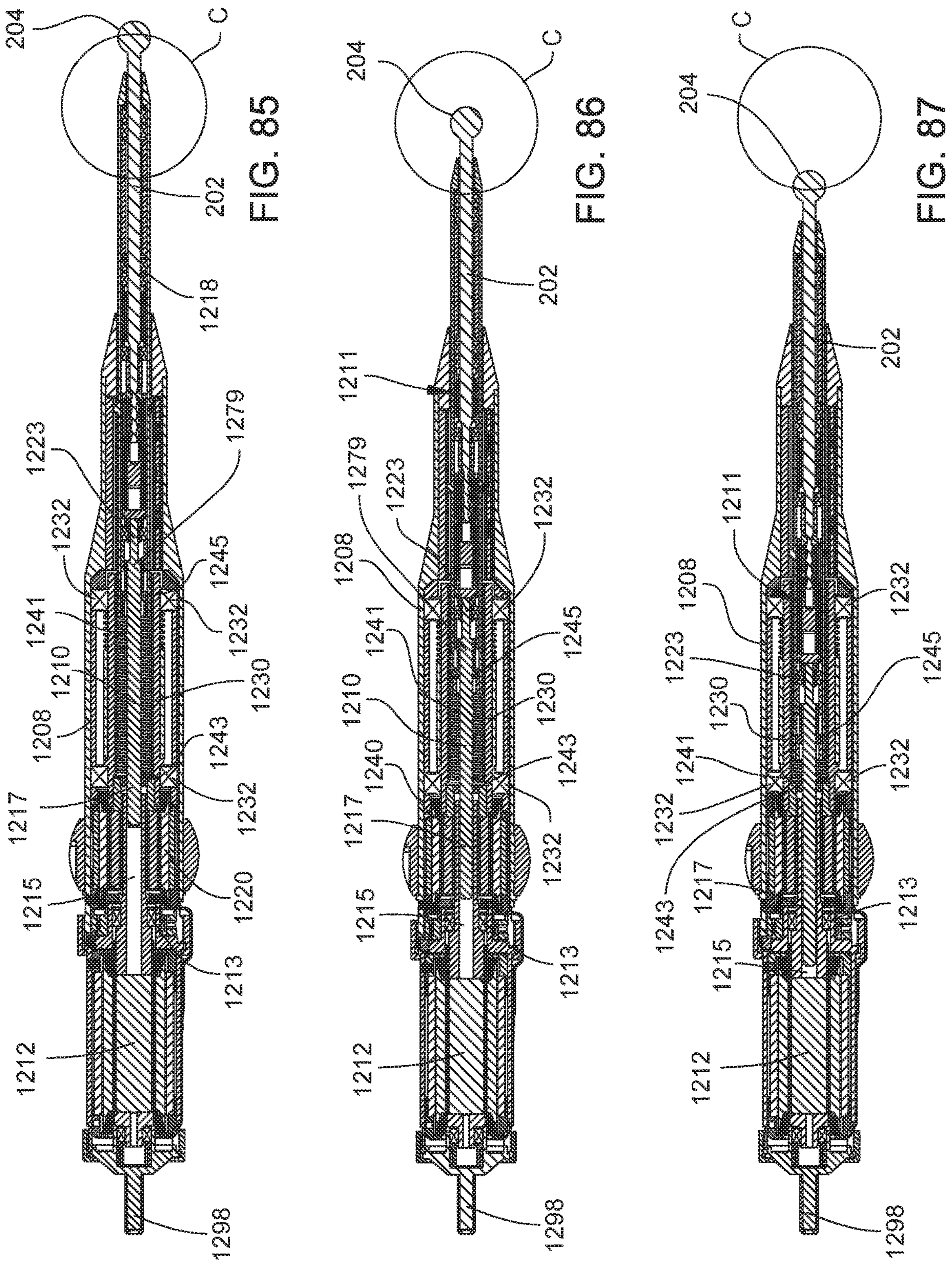
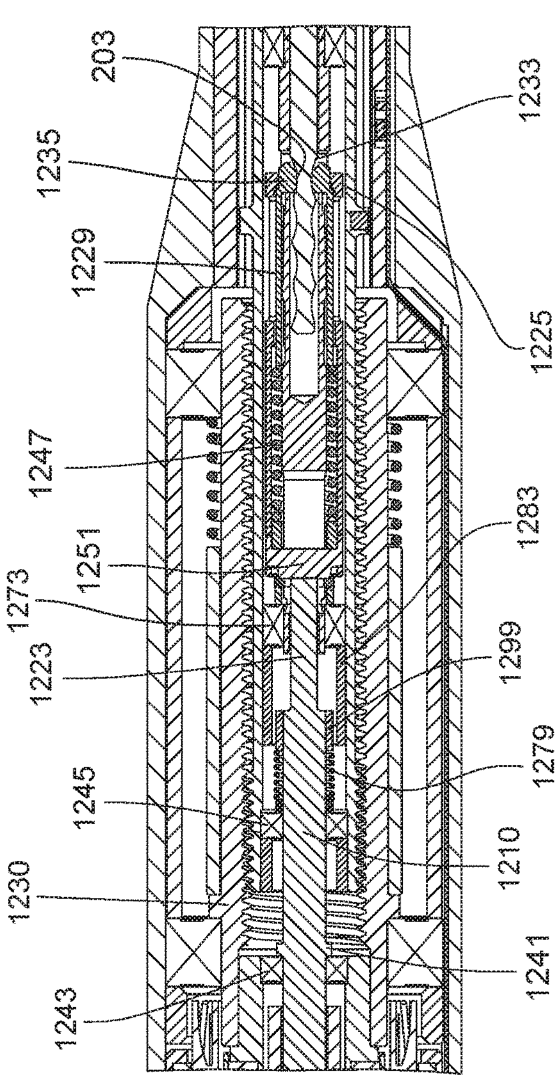


FIG. 85

FIG. 86

FIG. 87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1299
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1279
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1241

FIG. 88

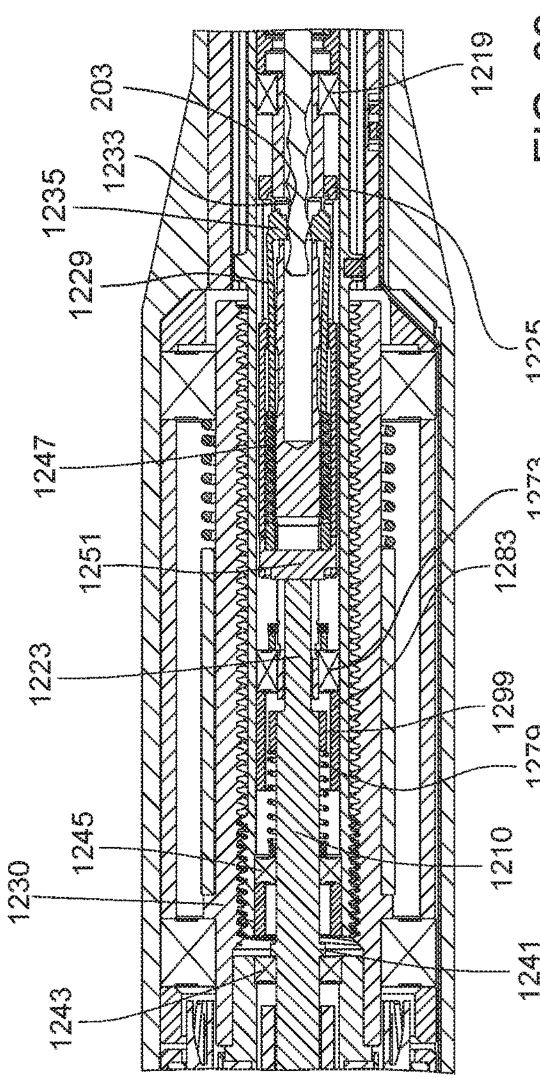
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FIG. 89

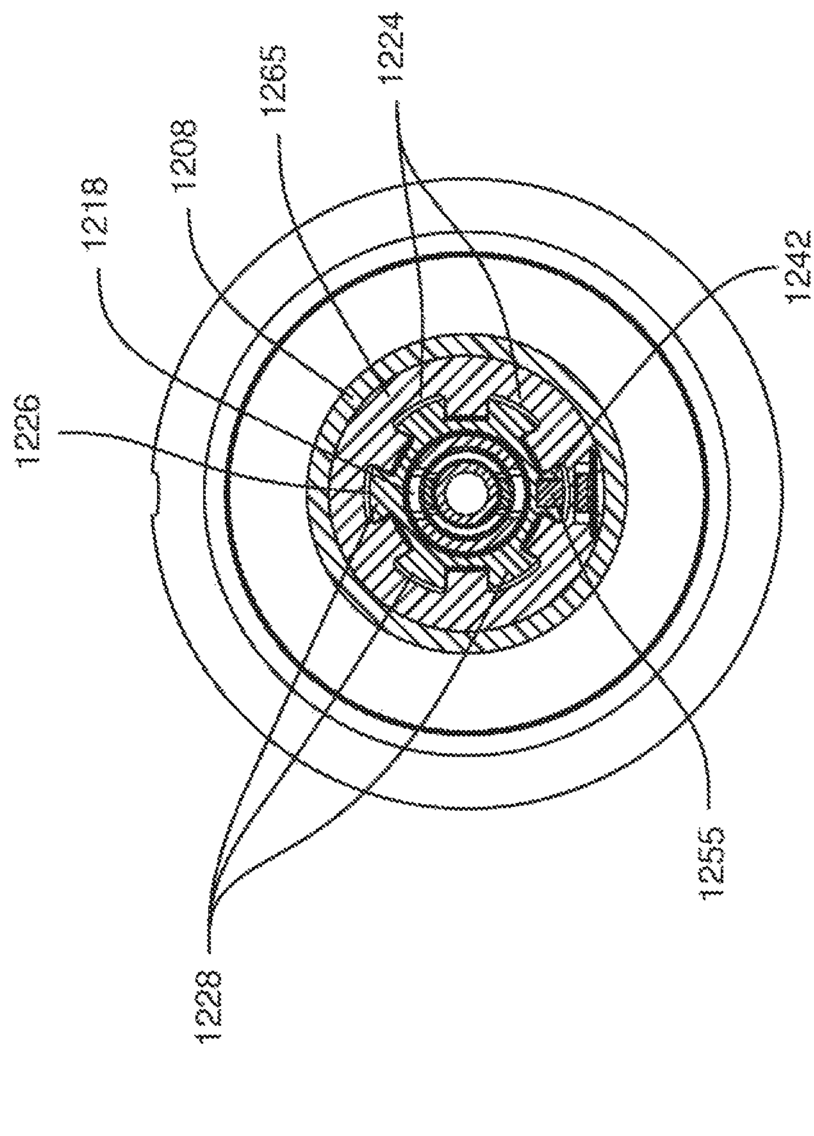


FIG. 90

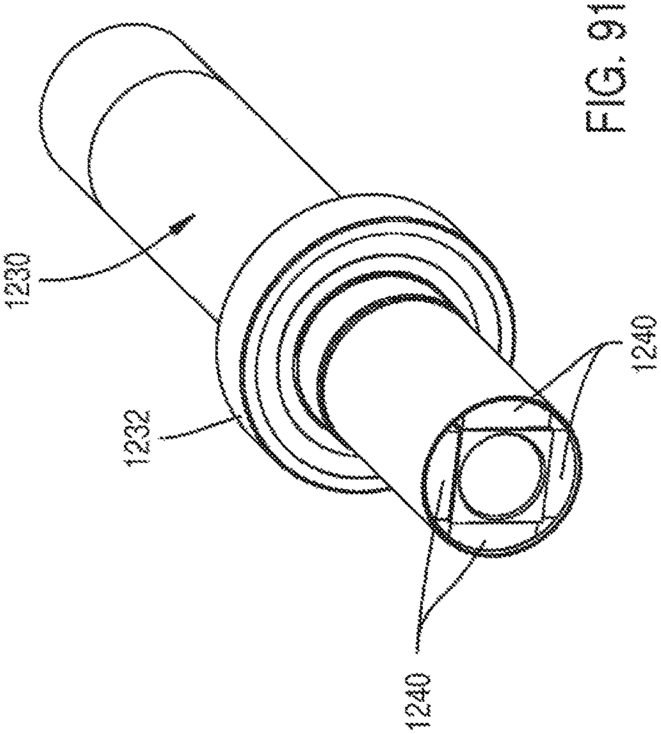


FIG. 91

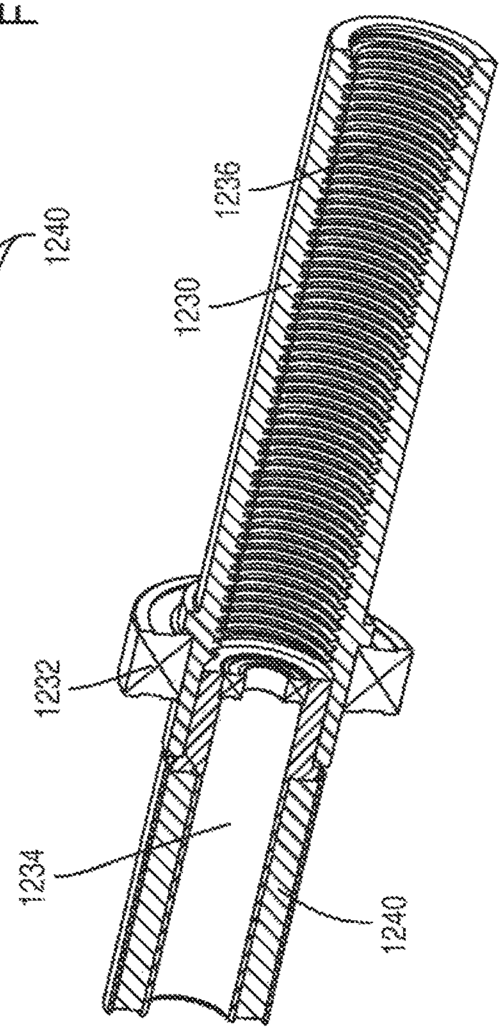
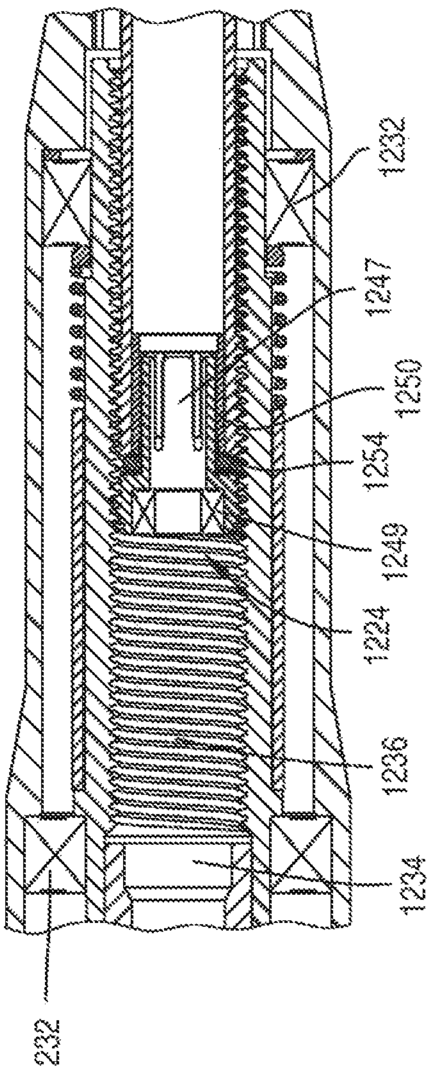


FIG. 92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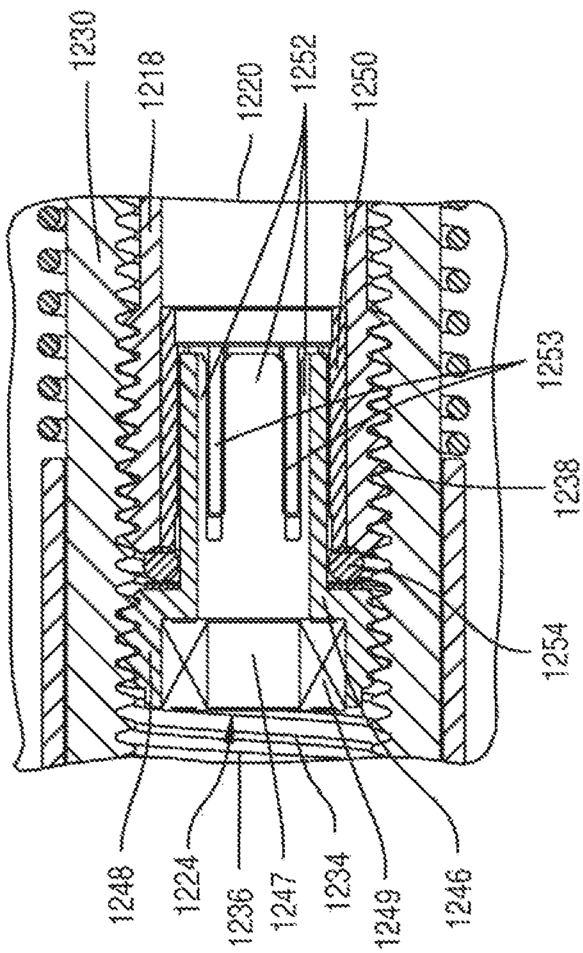
1234
1232

FIG. 93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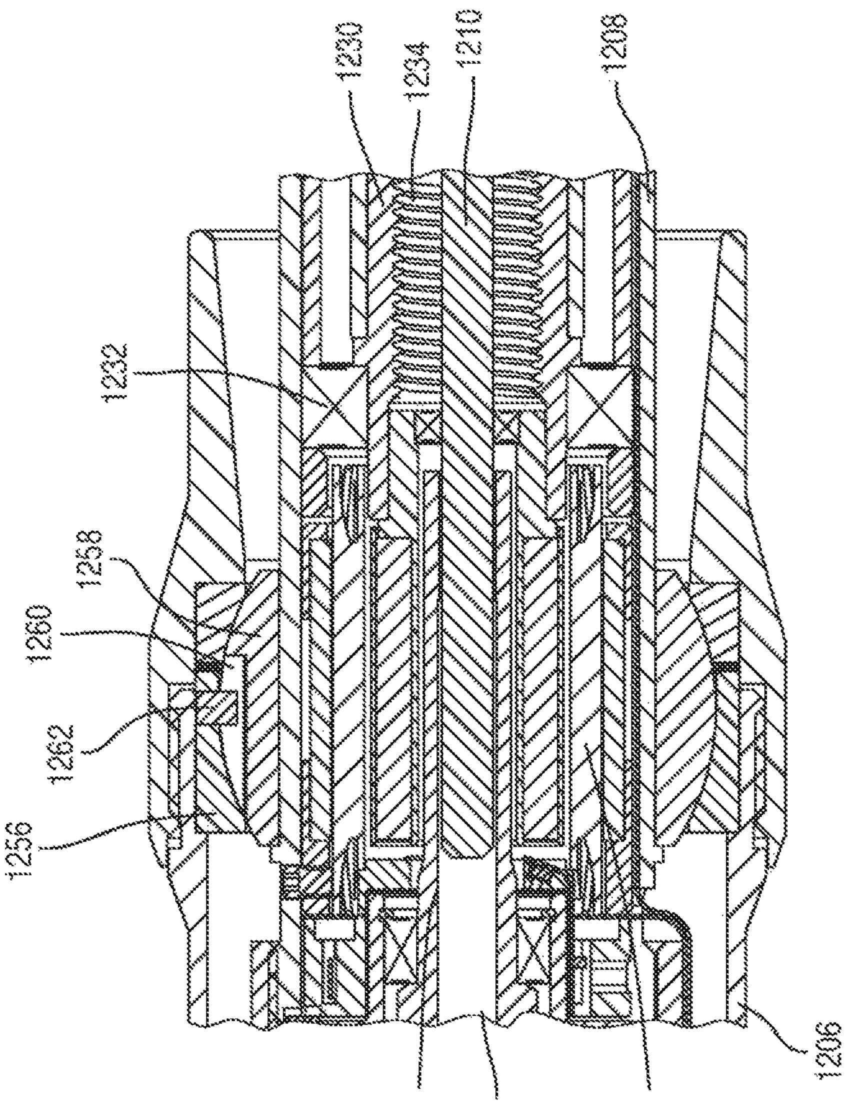
1224
1236
1247
1234
1249
1246

FIG. 94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1215
1240
1206

FIG. 95

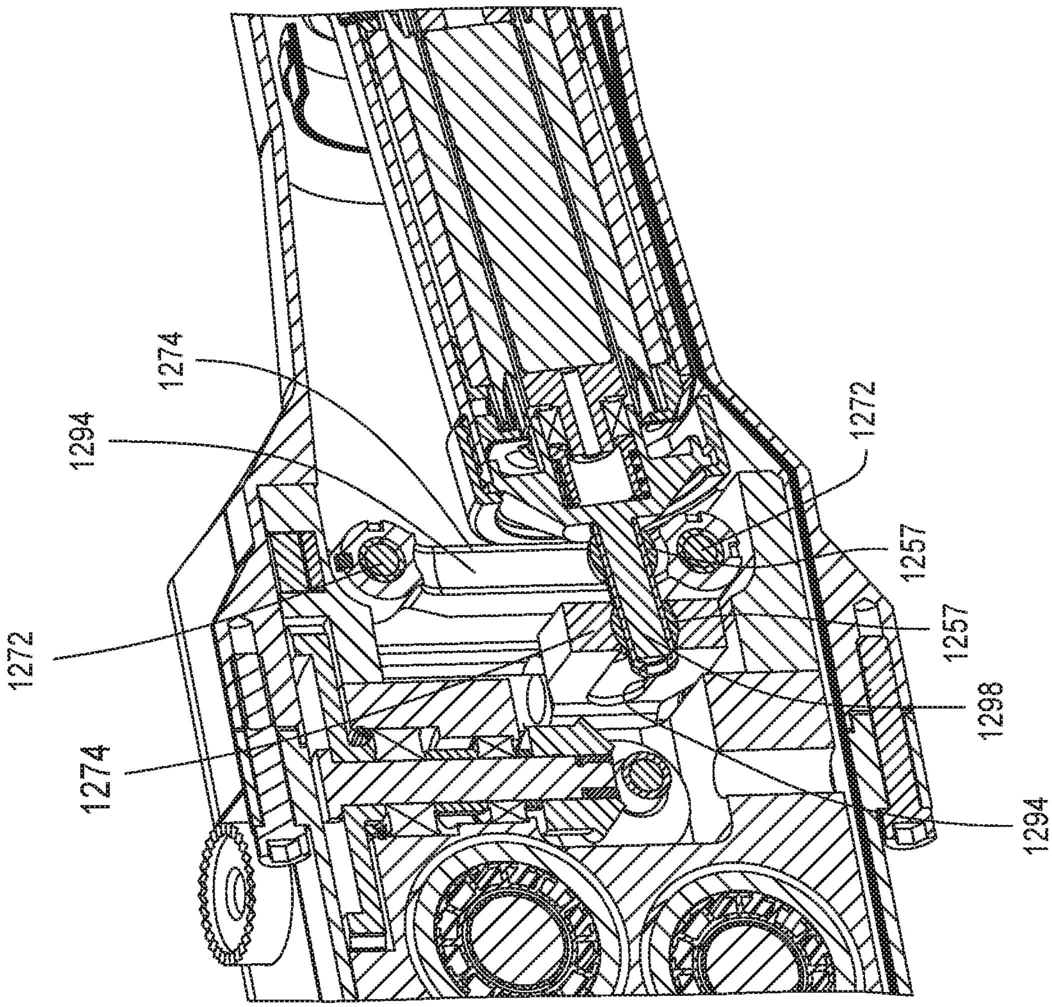


FIG. 96

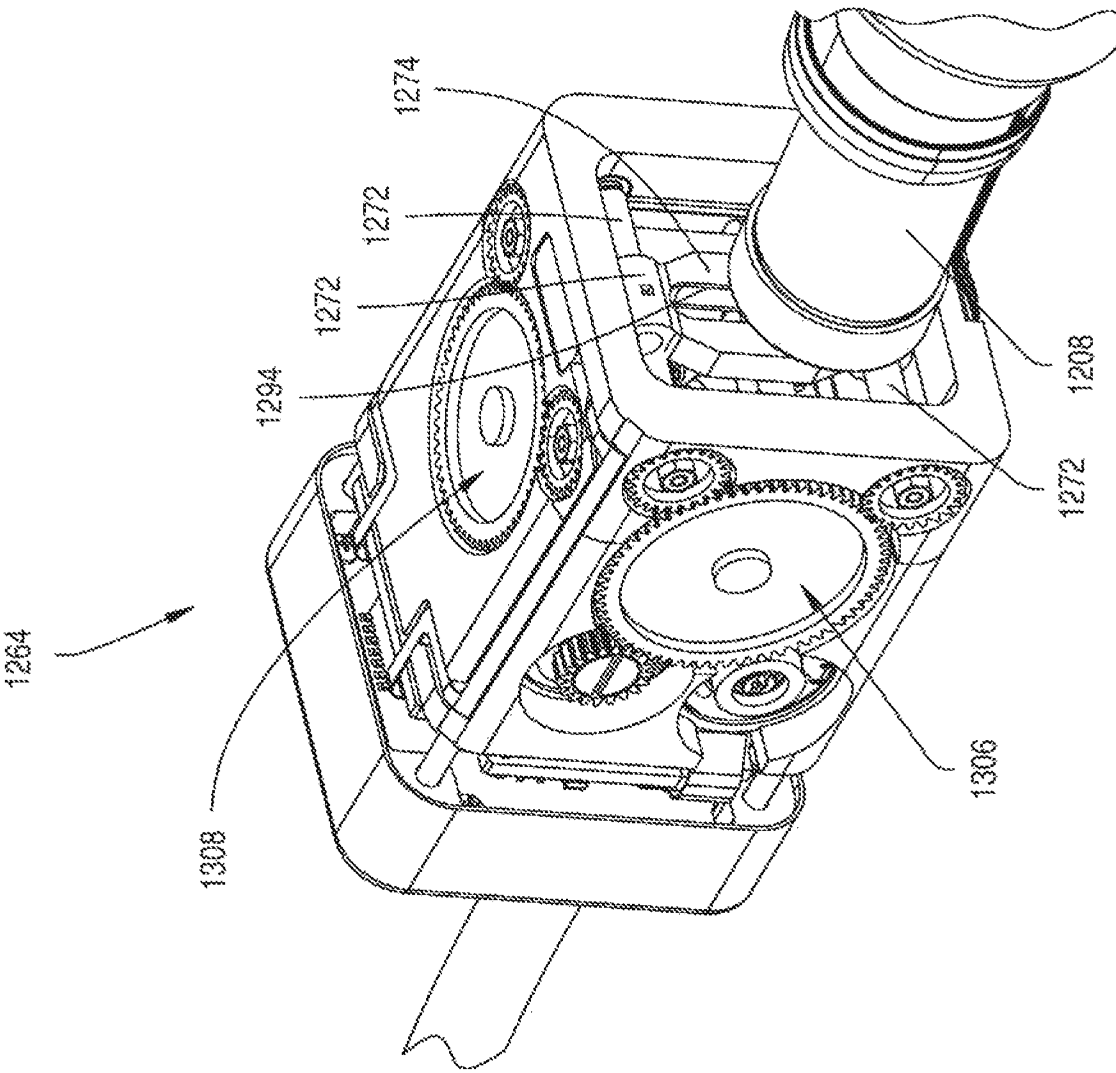


FIG. 97

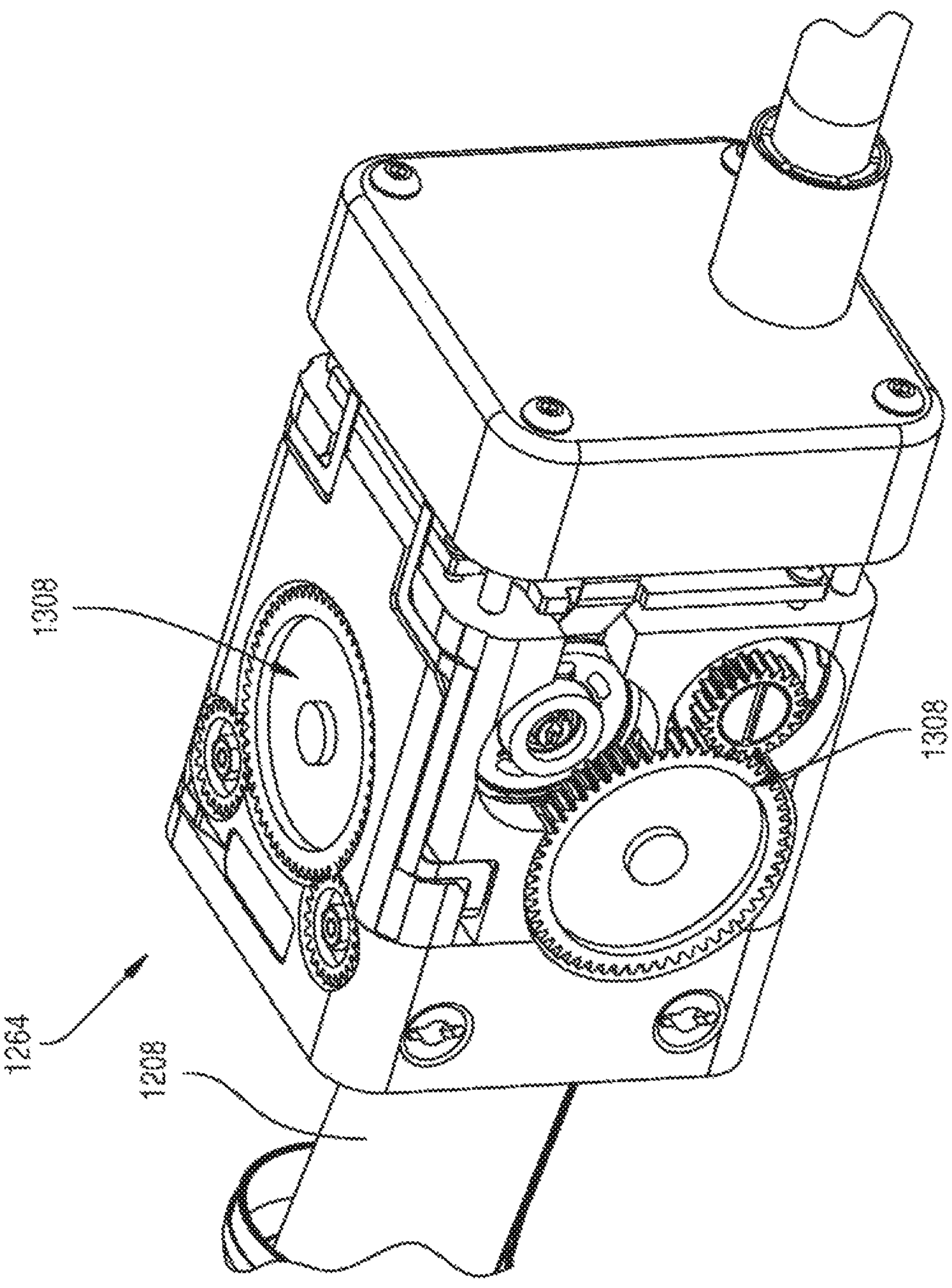


FIG. 98

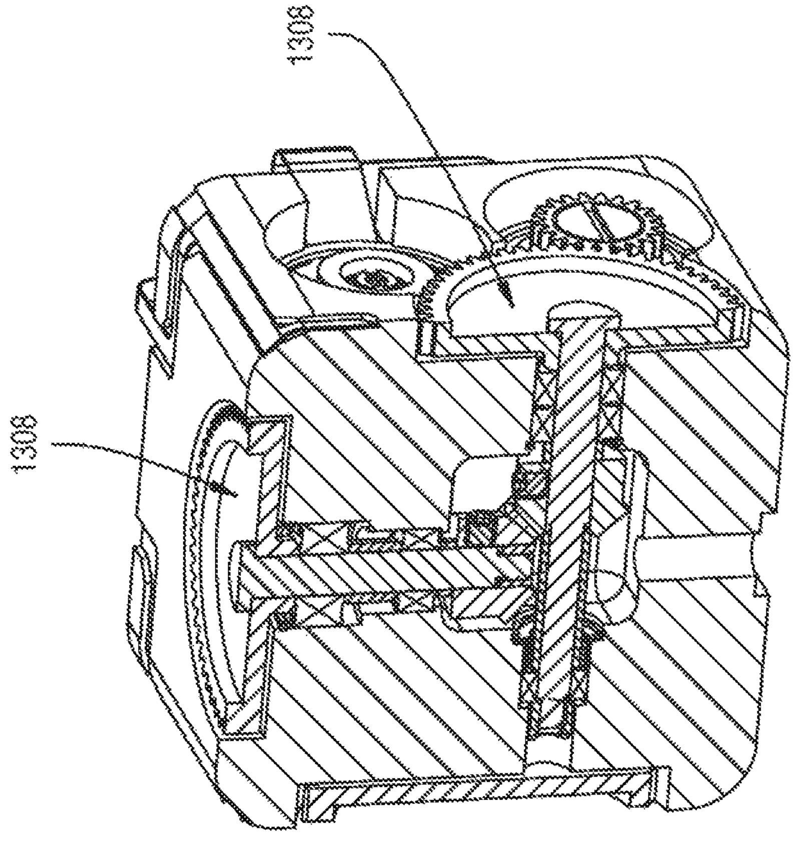


FIG. 99

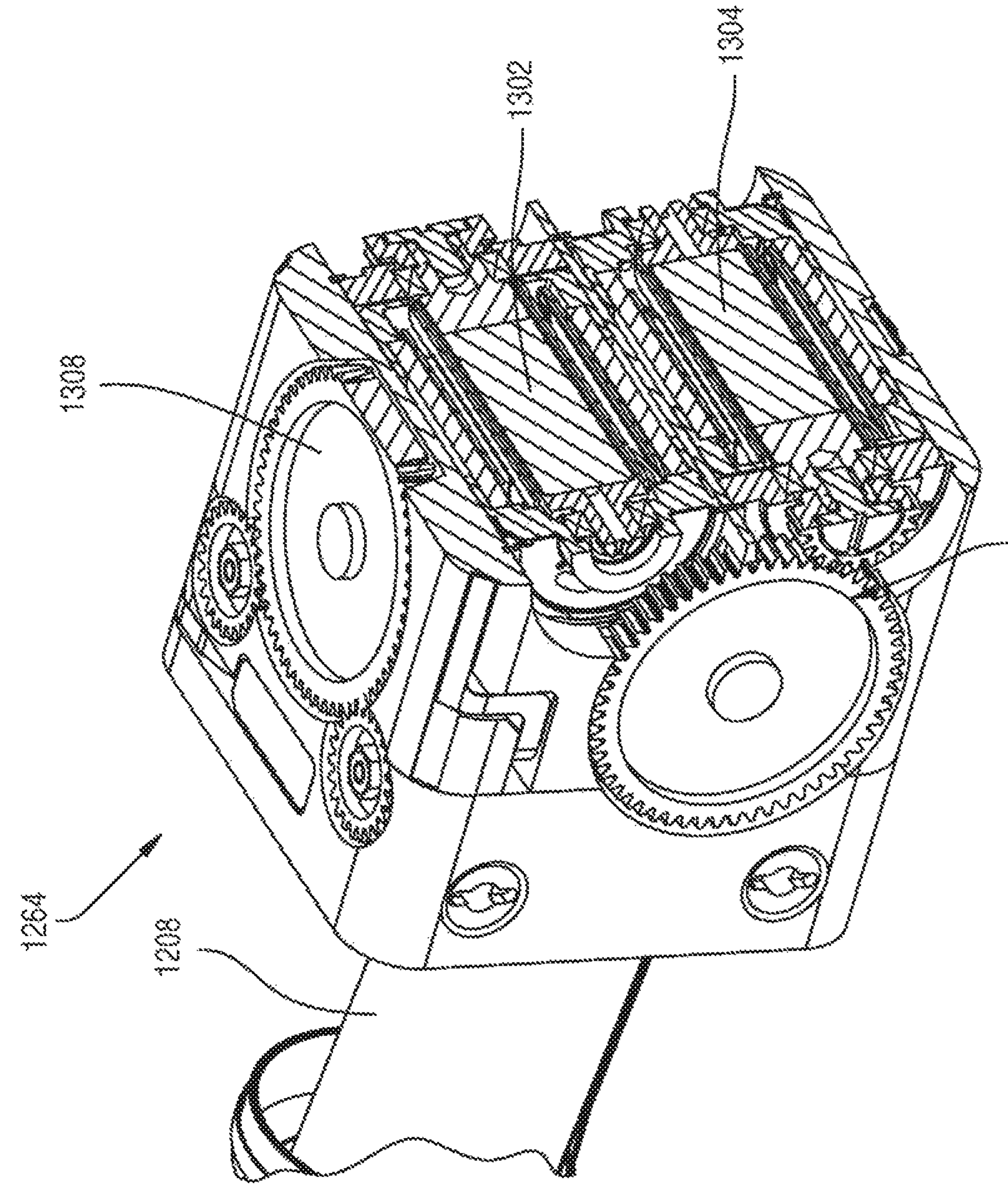
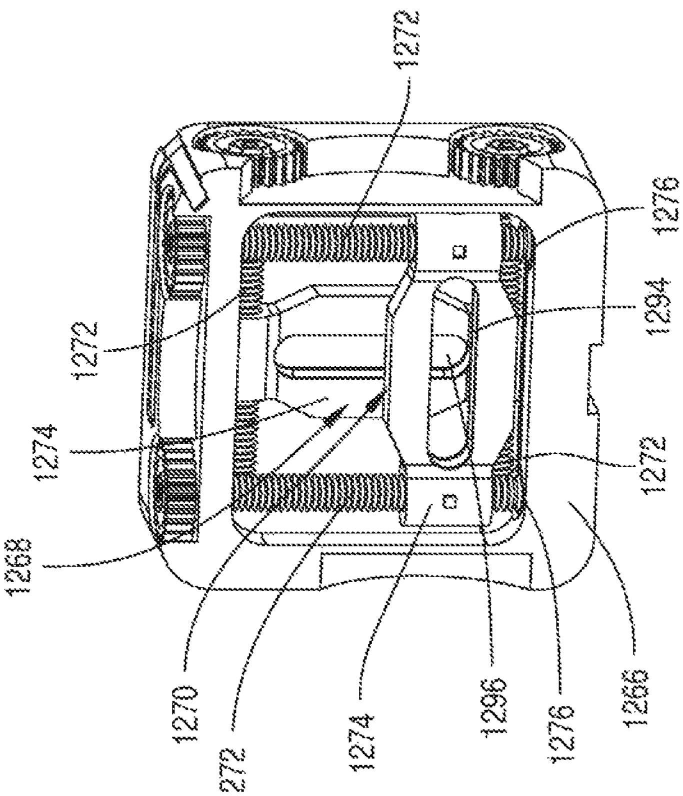


FIG. 100


1272
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1266

FIG. 101

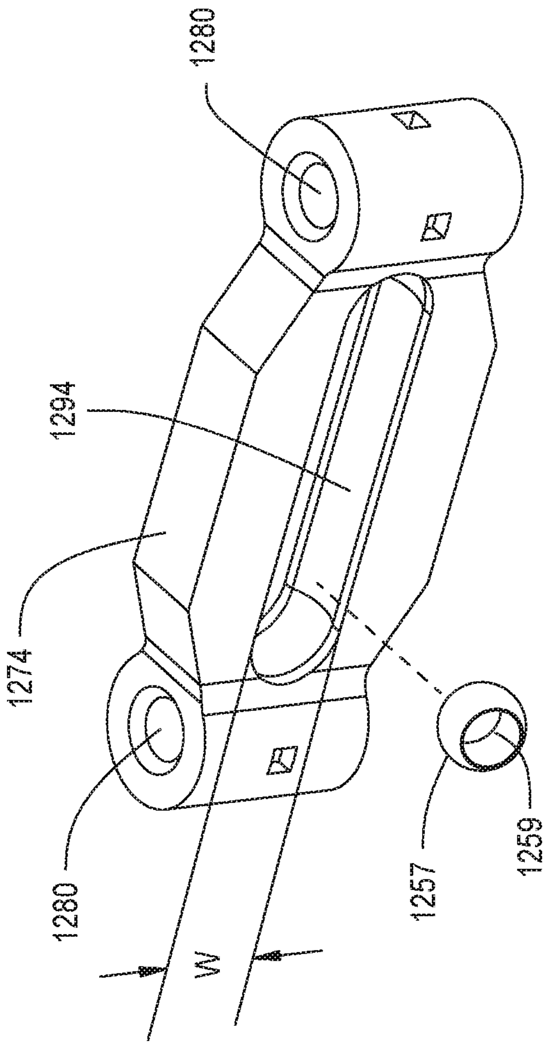

FIG. 102

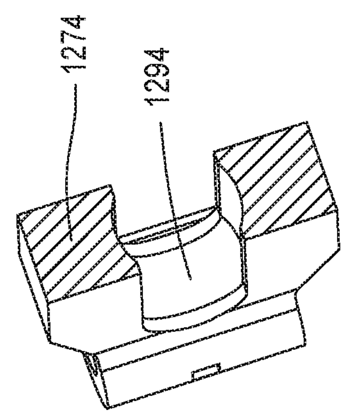

FIG. 103

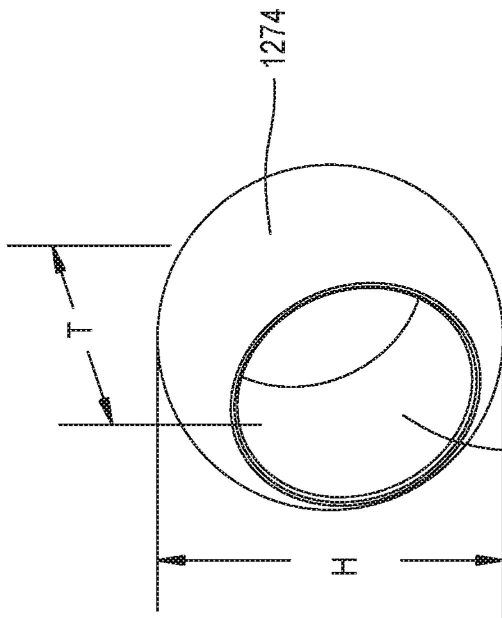

FIG. 104

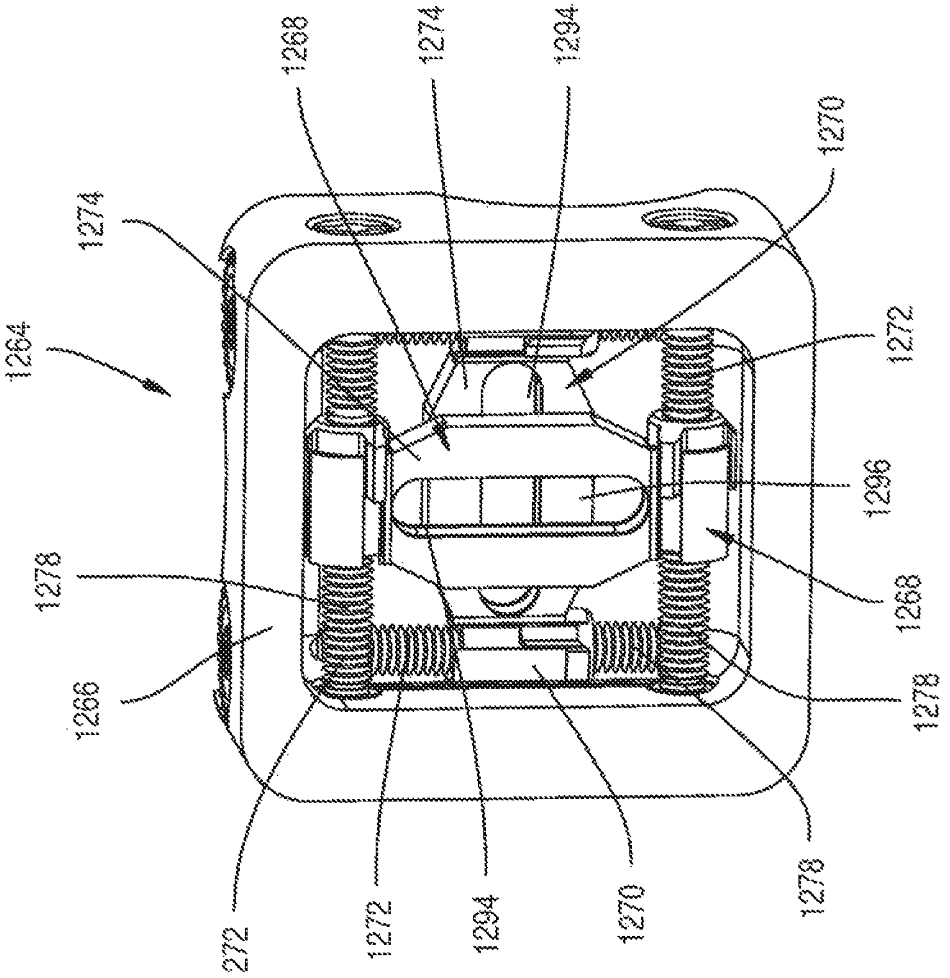

FIG. 105

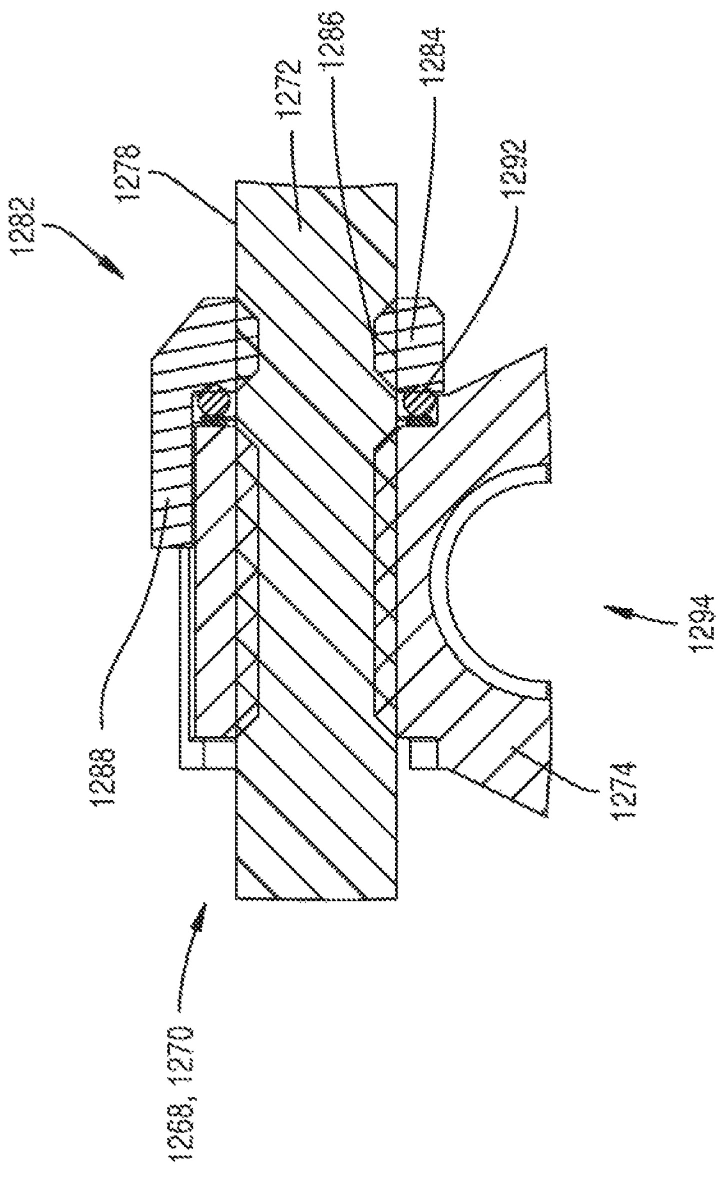

FIG. 106

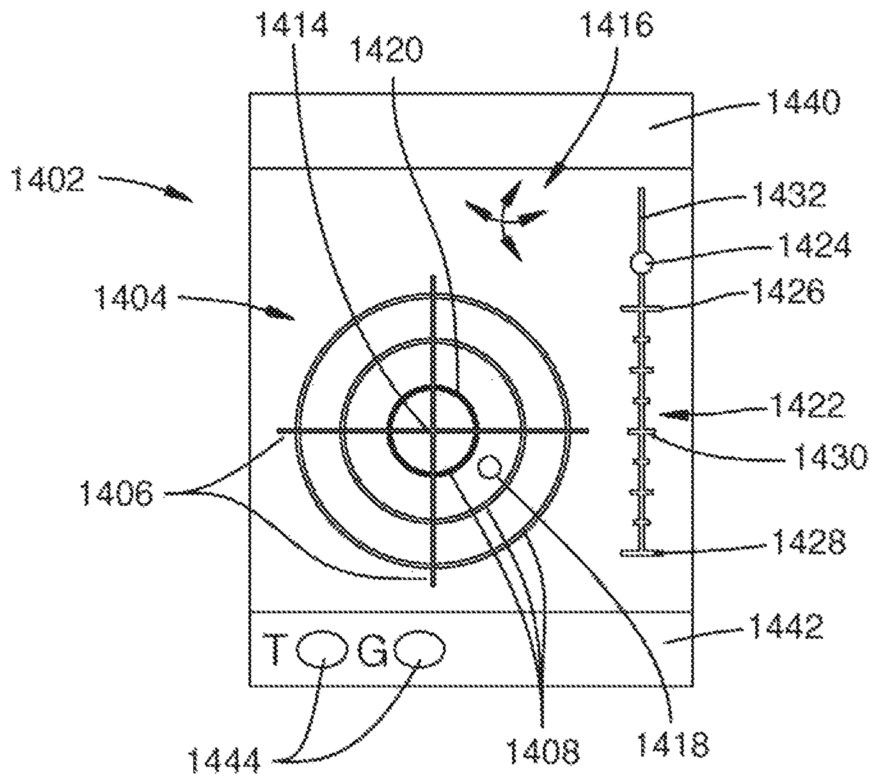

FIG. 107

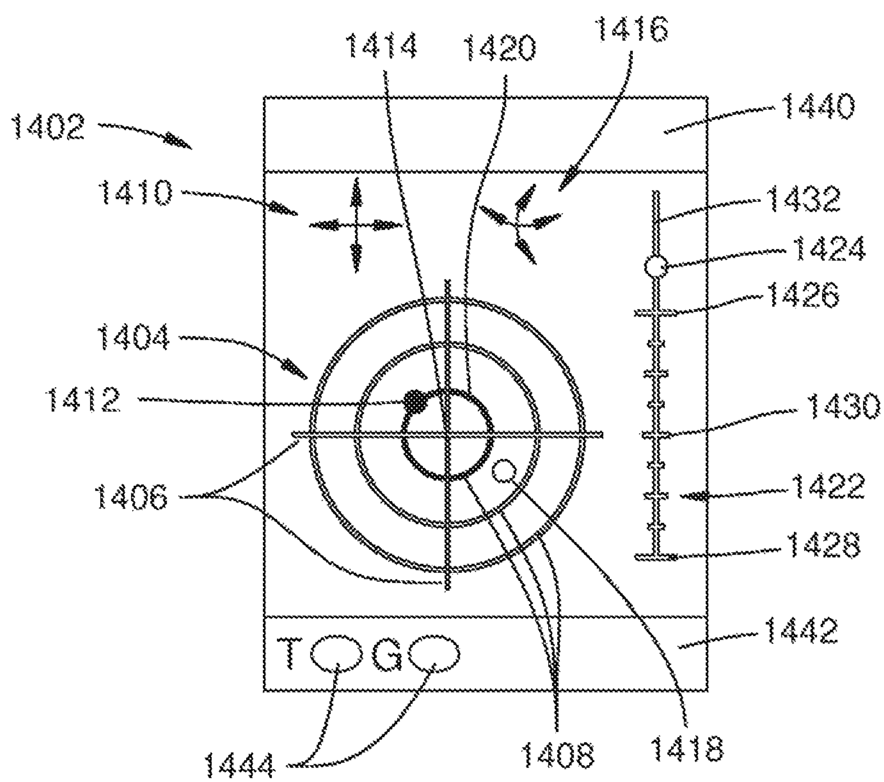

FIG. 108

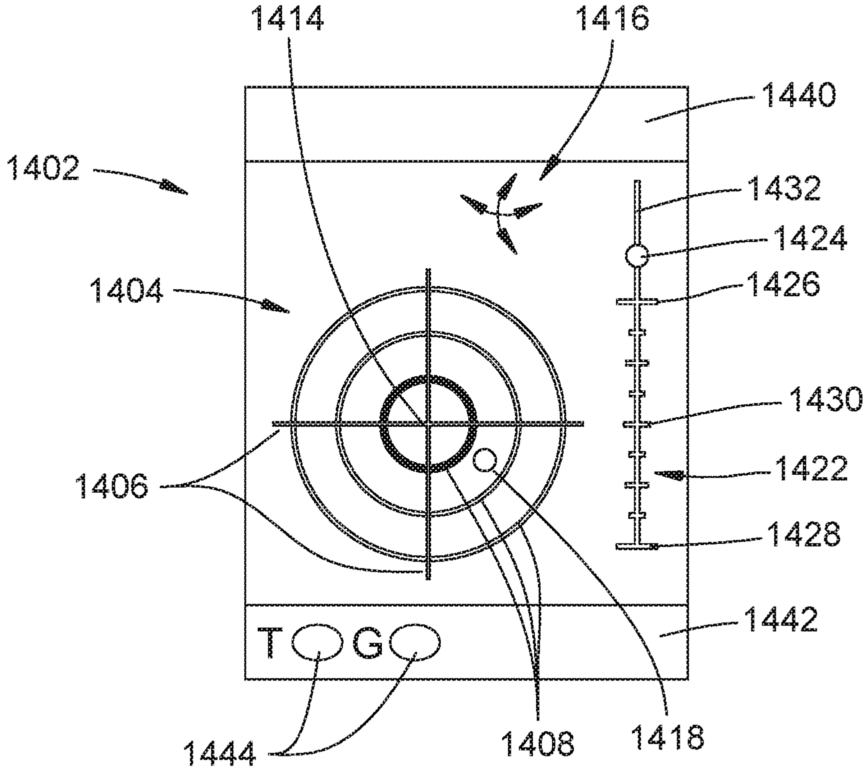

FIG. 109

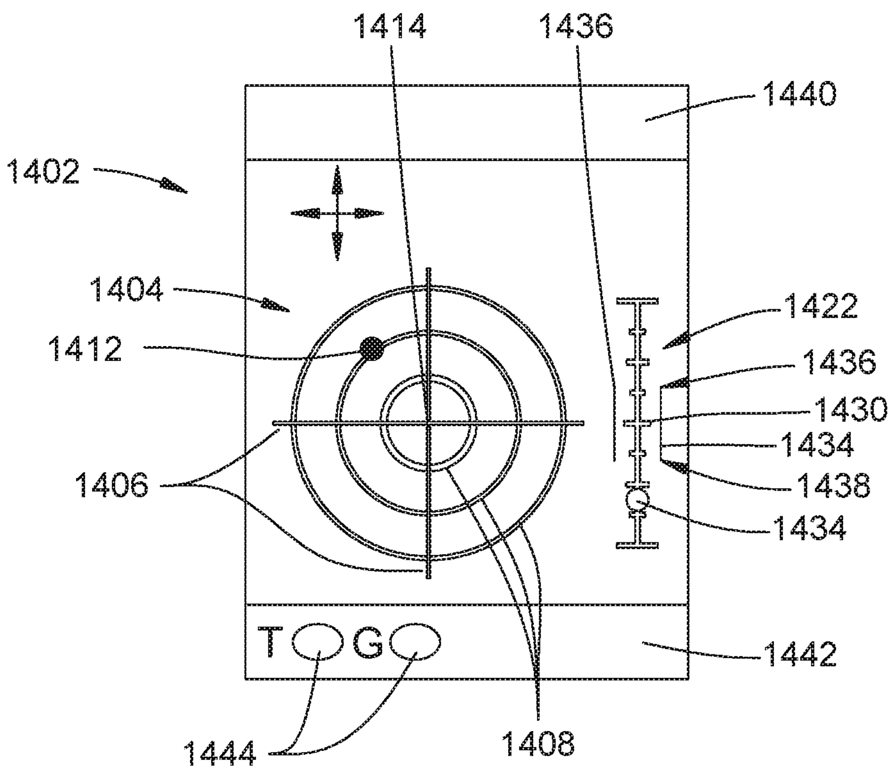

FIG. 110

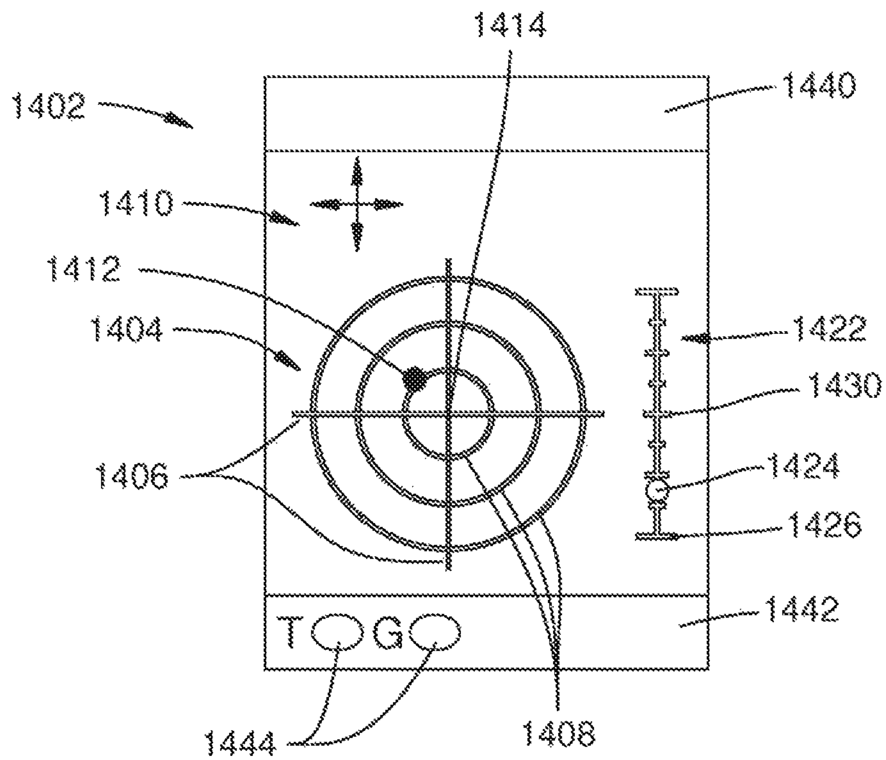
1414
1402
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FIG. 111

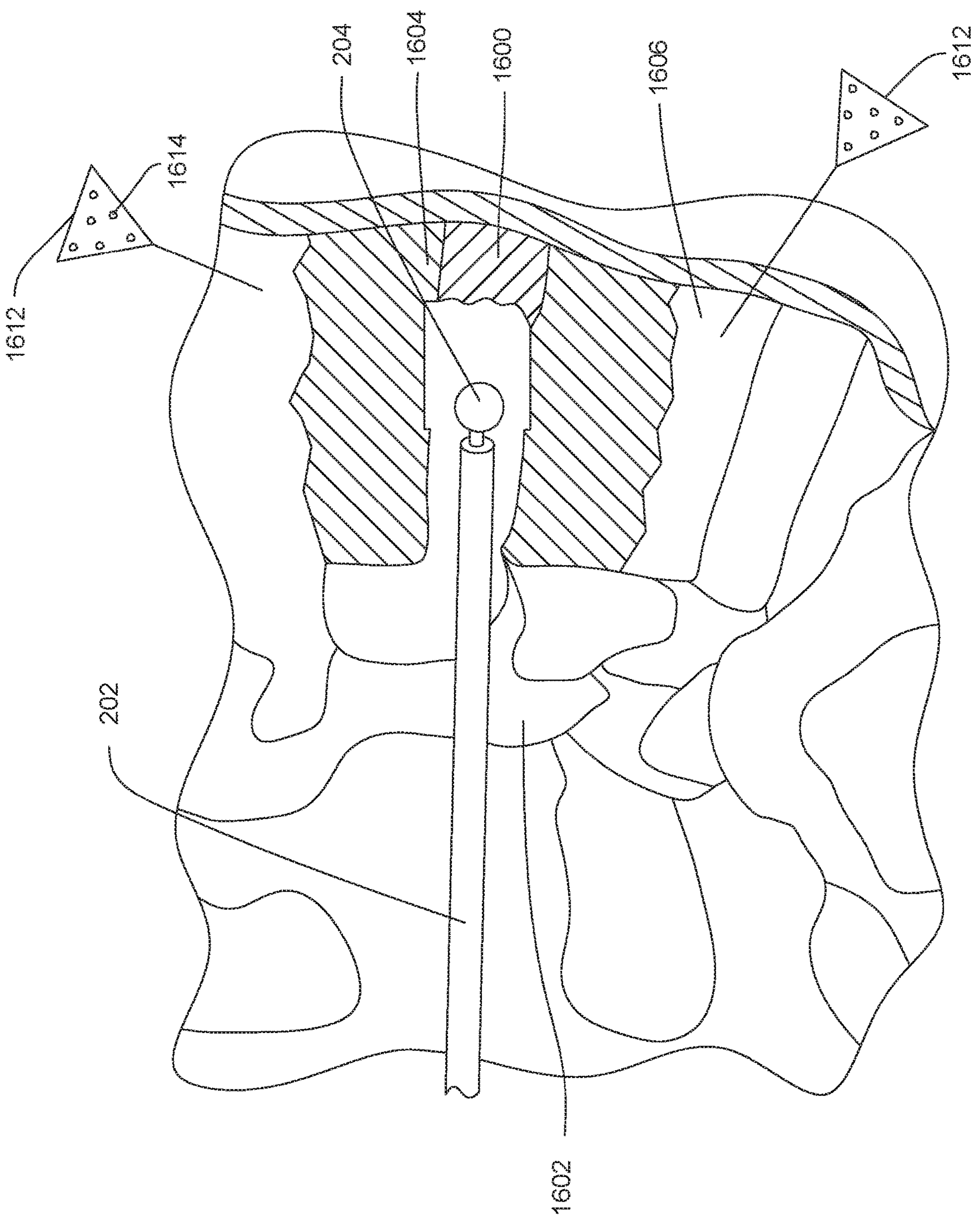

FIG. 112A

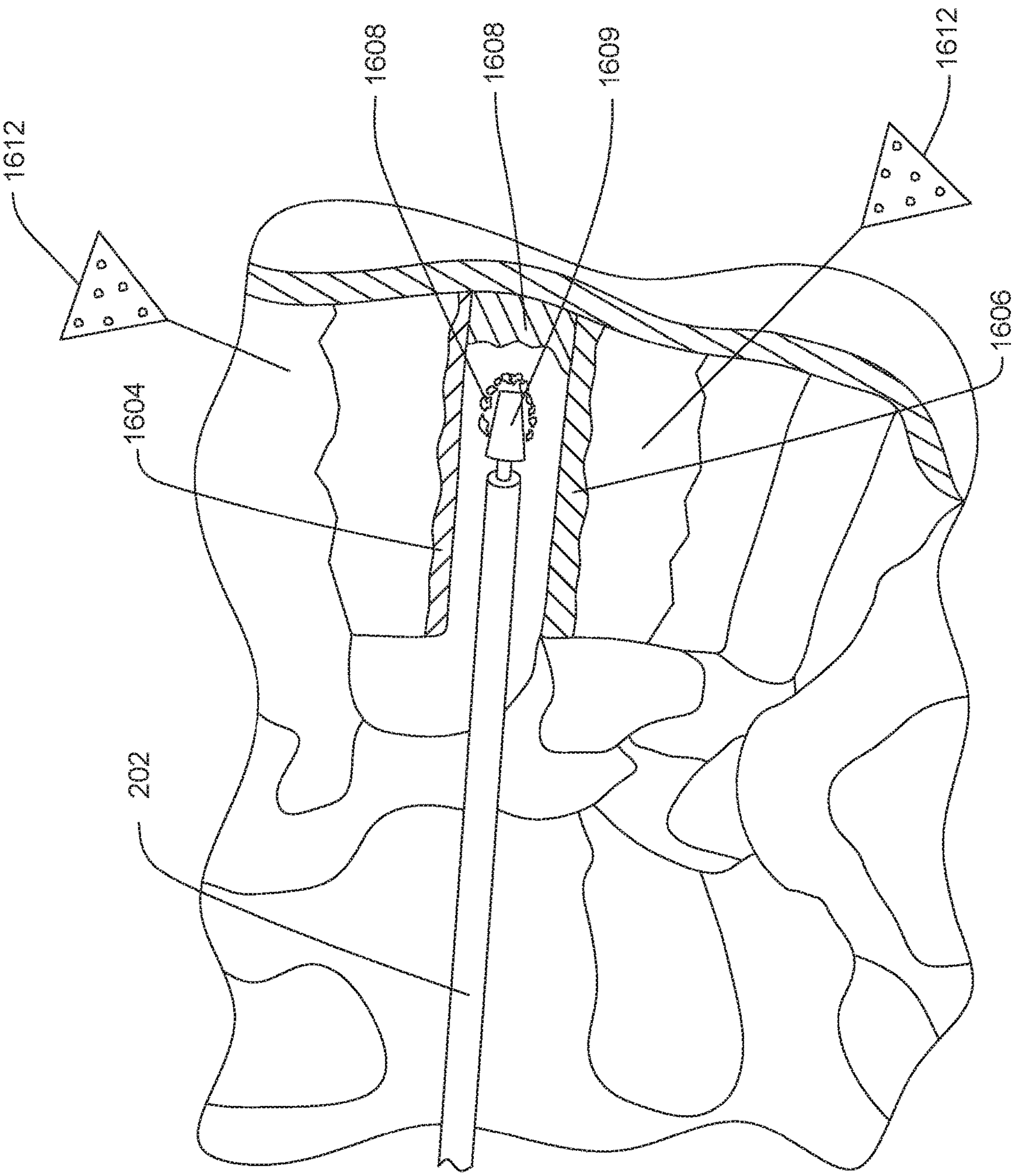

FIG. 112B

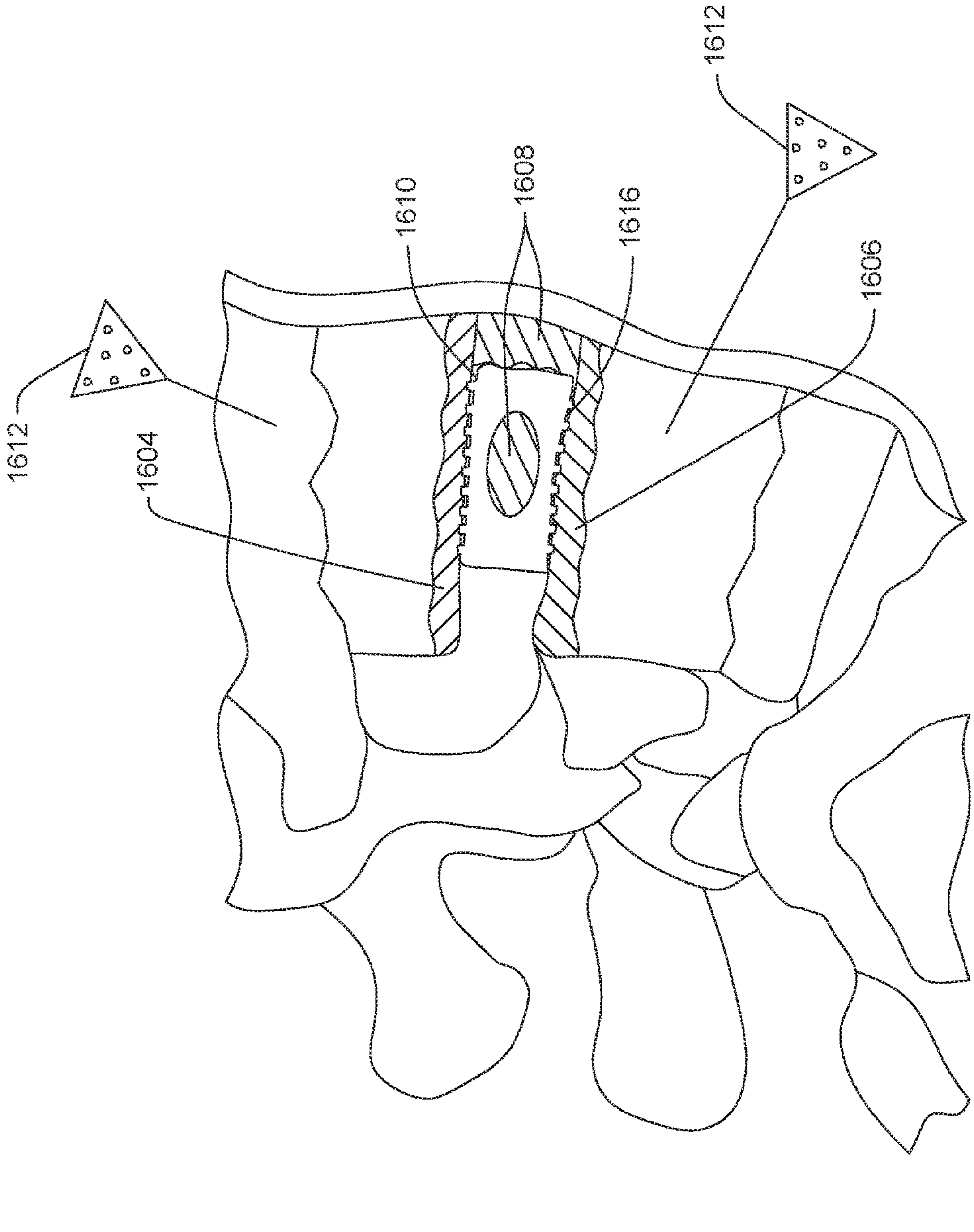

FIG. 112C

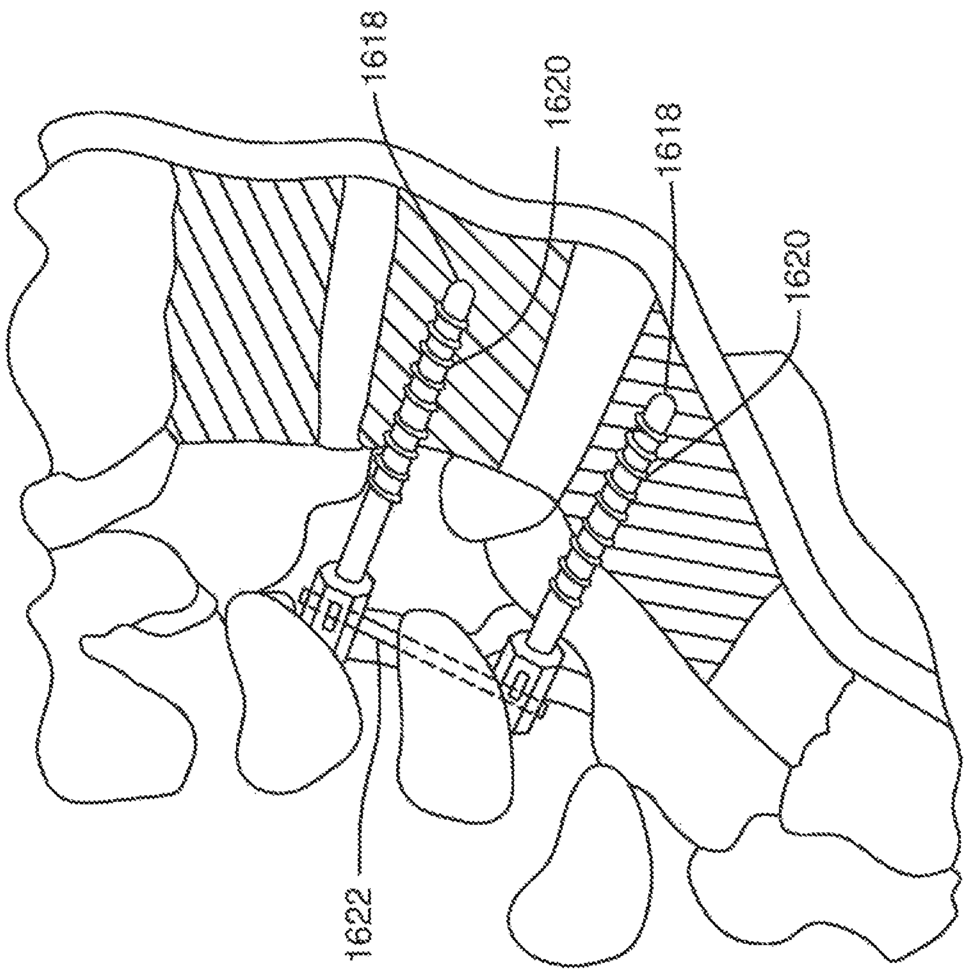

FIG. 112D

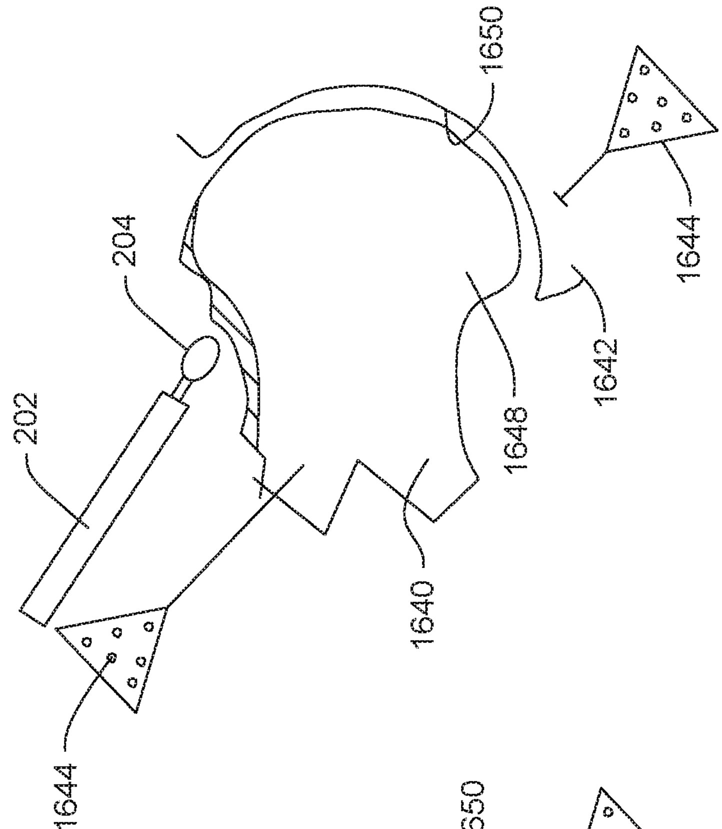

FIG. 113B

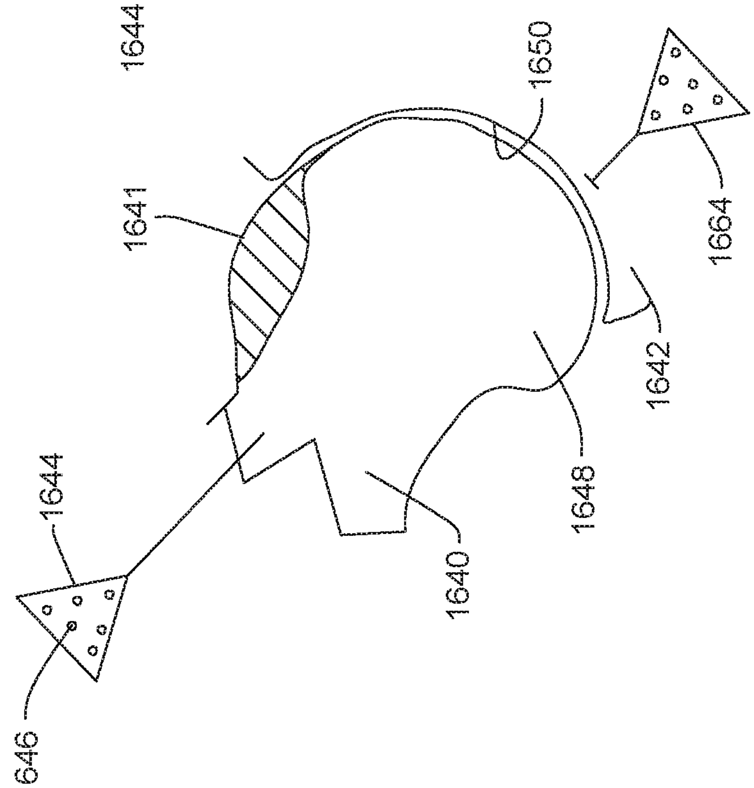

FIG. 113A

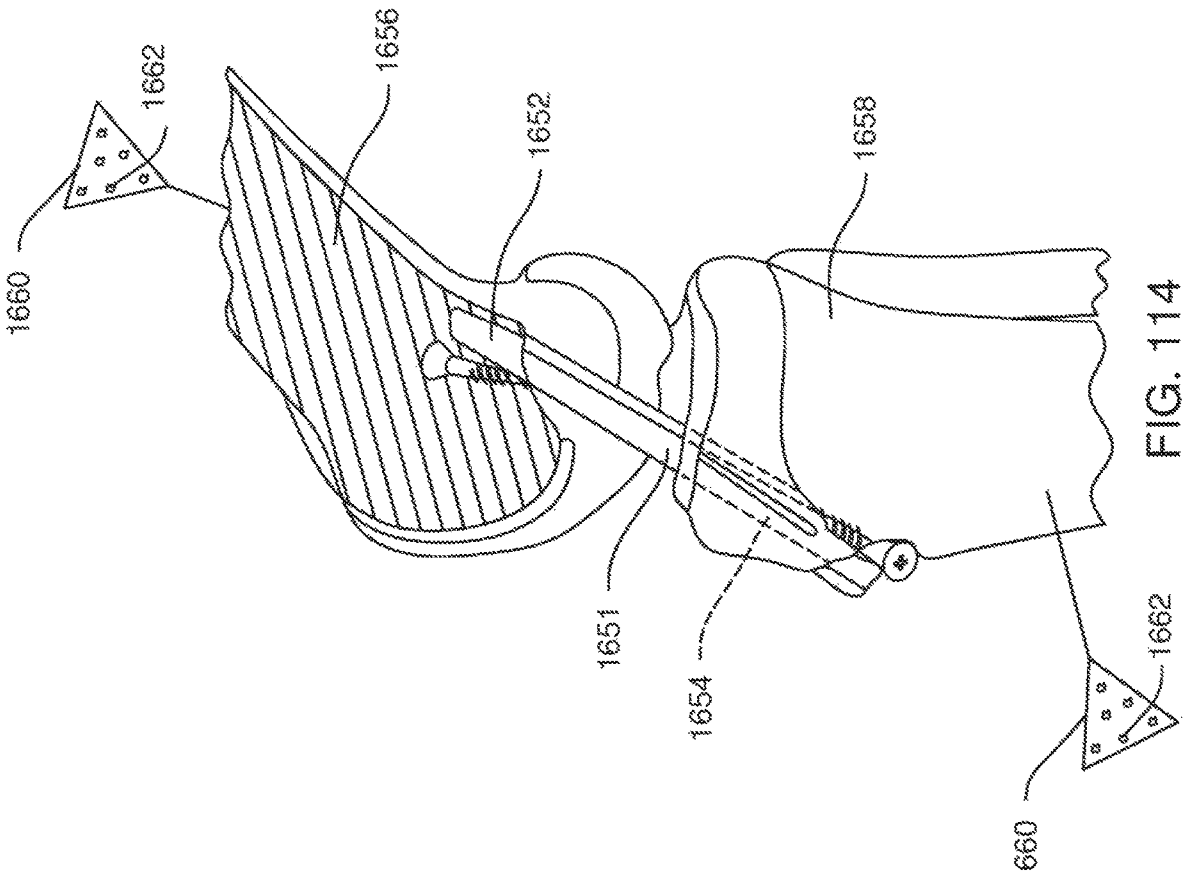

FIG. 114

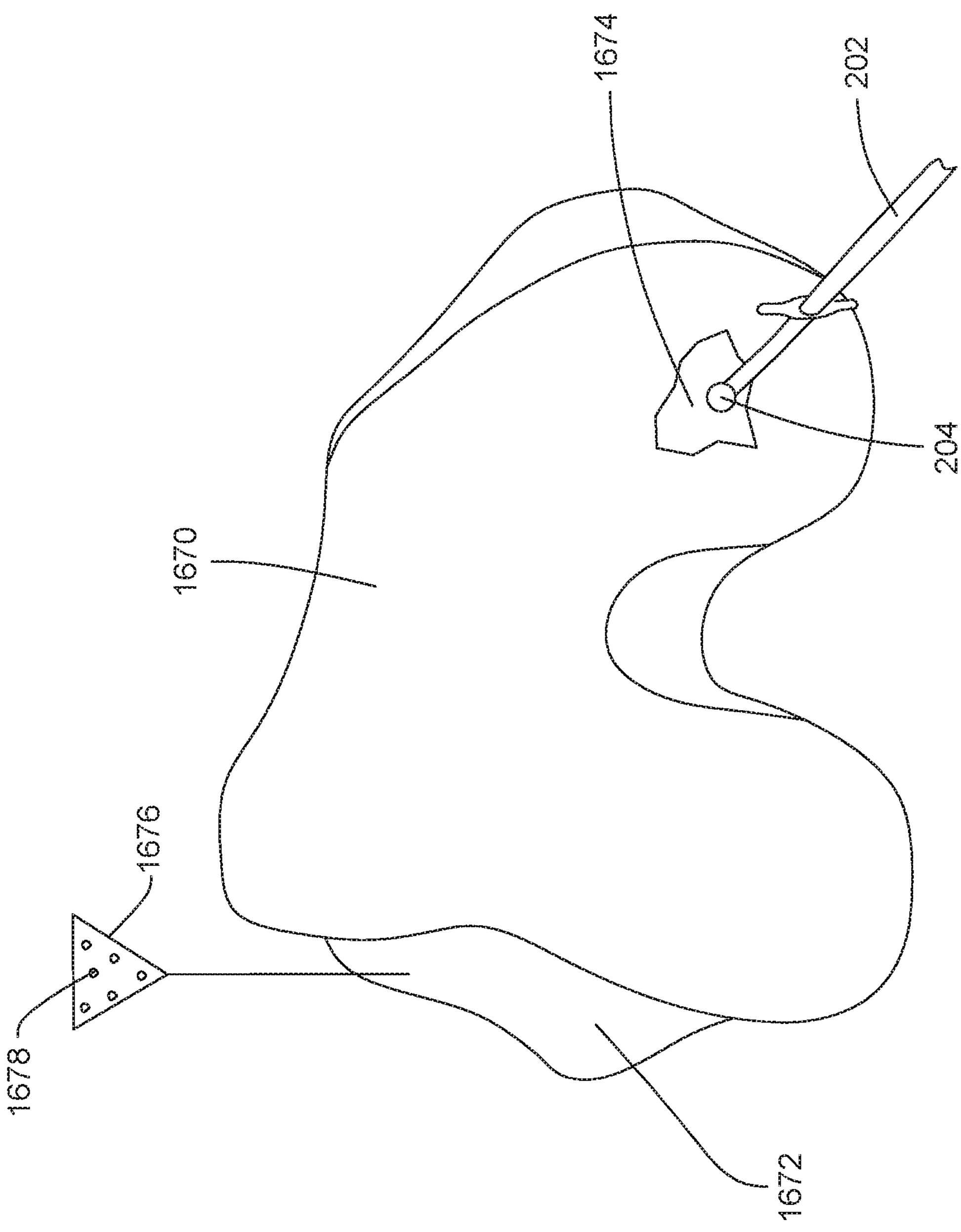

FIG. 115A

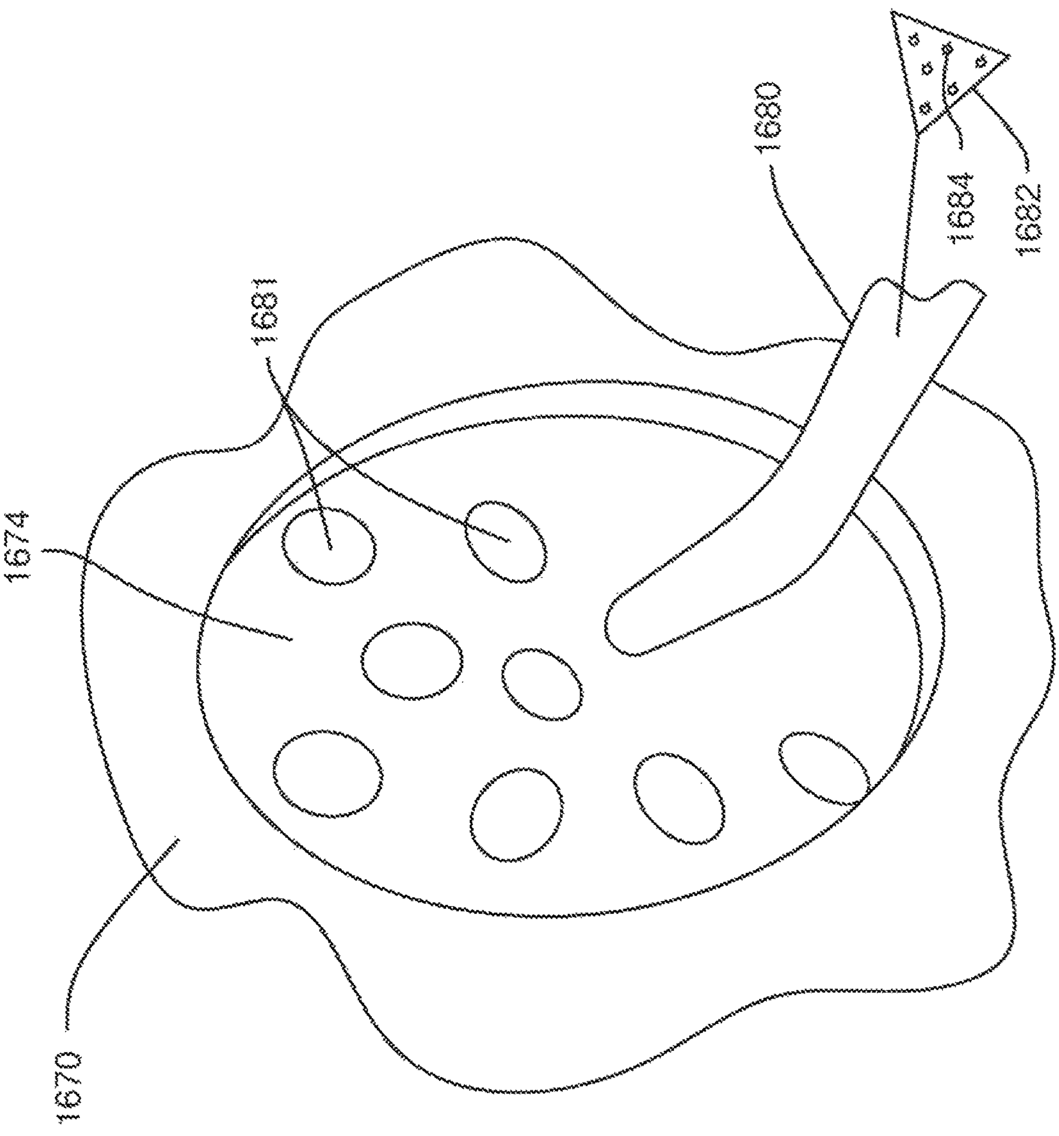

FIG. 115B

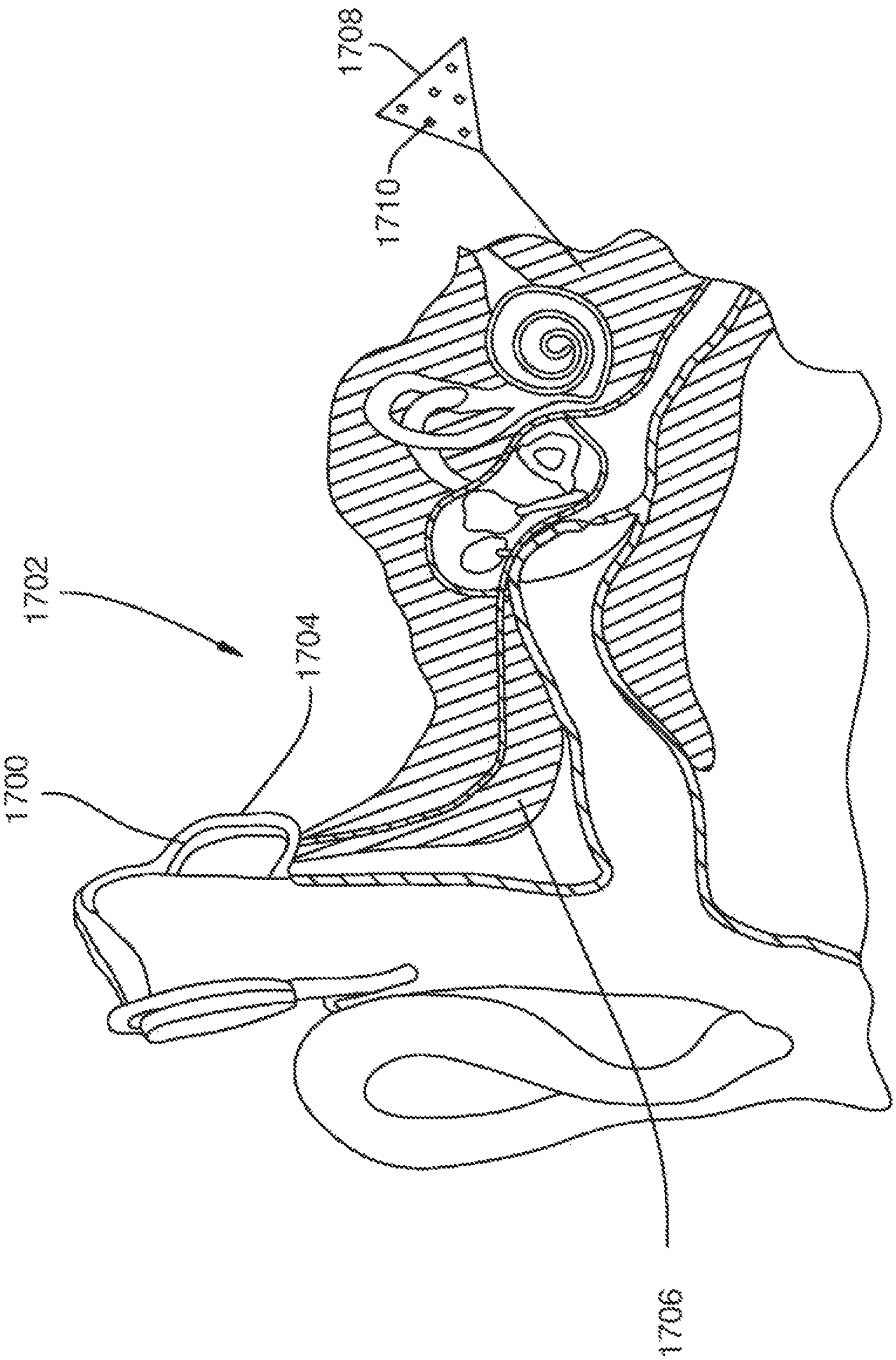

FIG. 116

METHODS OF PREPARING TISSUE OF A PATIENT TO RECEIVE AN IMPLANT

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 13/600,888 filed on Aug. 31, 2012, which claims priority to and all the benefits of U.S. Provisional Patent Application No. 61/530,614 filed on Sep. 2, 2011 and U.S. Provisional Patent Application No. 61/662,070 filed on Jun. 20, 2012, the contents of each being incorporated herein by reference in their entirety.

FIELD OF THE INVENTION

The present invention relates generally to hand-held surgical instruments, systems for tracking and controlling hand-held surgical instruments, and methods of use. The tracking and control system is used to keep a working part of the instrument in a desired relationship to a boundary. The system controls the position of a cutting accessory integral with the instrument when the accessory is applied to tissue during a medical/surgical procedure.

BACKGROUND OF THE INVENTION

Tracking systems (also known as navigation systems) assist surgeons during surgeries that require the precise locating of instruments. Such surgeries include neurosurgery and orthopedic surgery. The tracking system tracks the position and orientation of an instrument during the procedure and often displays the position and/or orientation of the instrument on a monitor in conjunction with a preoperative image or an intraoperative image of the patient (preoperative images are typically prepared by MRI or CT scans, while intraoperative images may be prepared using a fluoroscope, low level x-ray or any similar device). Alternatively, some systems are image-less in which the patient's anatomy is instead registered and mathematically fitted with an anatomical model.

Prior art tracking systems typically employ a camera that detects a tracking device located on the instrument. The tracking device has a plurality of optical markers such as light emitting diodes (LEDs) to determine the position and orientation of the instrument. The position of the instrument usually correlates to the coordinates of a working end of the instrument in three-dimensional space, the x, y, z or Cartesian coordinates, relative to the camera. The orientation of the instrument means the pitch, roll, and yaw of the instrument. When both the position and the orientation of the instrument are defined, the relative position of that instrument is known to the tracking system.

Orthopedic surgeons have been using tracking systems for some time to assist in properly locating and positioning cutting jigs. Cutting jigs are used to resect bone for the purpose of preparing joints to accept replacement implants. The time required to position and secure a cutting jig can appreciably add to the overall time required to perform a joint replacement surgical procedure. It should be appreciated that the cutting jig must be accurately positioned. Imprecise positioning of a cutting jig can contribute to a less than ideal surgical outcome. As a result, there has been a movement to eliminate the use of cutting jigs. Instead, surgeons would rely solely on tracking the instrument to ensure that the cutting portion of the instrument does not stray beyond a predefined boundary.

In such tracking systems both the instrument and the material being cut are outfitted with trackers such that the tracking system can track both the position and orientation of the instrument and the material being cut such as a bone. The instrument is held by a robot or other articulation mechanism that provides some form of mechanical constraint to movement. This constraint limits the movement of the instrument to within a predefined boundary. If the instrument strays beyond the predefined boundary, a control is sent to the instrument to stop cutting. Such systems are shown in U.S. Pat. No. 5,408,409 to Glassman et al.

It has also been proposed in the prior art that the instrument be used free hand without the aid of cutting jig, guide arm or other constraining mechanism to establish the location to which the cutting implement at the end of the instrument is applied. See, for example, U.S. Pat. No. 6,757,582 to Brisson et al.

SUMMARY AND ADVANTAGES

The present invention provides an instrument for treating tissue during a medical procedure. The instrument comprises a hand-held portion for being manually supported and moved by a user. A working portion is movably coupled to the hand-held portion. A plurality of actuators are operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion. A tracking device is attached to the hand-held portion for tracking the instrument. A drive mechanism is coupled to the working portion for rotating the working portion about a rotational axis. The drive mechanism moves in at least one degree of freedom relative to the hand-held portion.

The present invention also provides an instrument for treating tissue during a medical procedure, as described in this paragraph. The instrument comprises a hand-held portion for being manually supported and moved by a user. A working portion is movably coupled to the hand-held portion and includes a distal tip. A plurality of actuators are operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion. A tracking device is attached to the hand-held portion for tracking the instrument. The distal tip of the working portion is capable of a total displacement of at least 0.2 inches (0.508 cm) in each of the plurality of degrees of freedom.

The present invention also provides a method for treating tissue during a medical procedure using an instrument having a hand-held portion, a working portion, a plurality of actuators for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion, a plurality of sensors for sensing positions of the working portion relative to the hand-held portion, and a control system for controlling the instrument. The method comprises the steps of: manually supporting and moving the hand-held portion during the medical procedure to treat the tissue of a patient with the working portion; and operating the control system so that the control system establishes a home position of the working portion relative to the hand-held portion and tracks deviation of the working portion from the home position as the working portion moves in one or more of the plurality of degrees of freedom relative to the hand-held portion in order to maintain a desired relationship to a virtual boundary associated with the tissue during the medical procedure.

The present invention also provides a method for treating tissue during a medical procedure using an instrument, as described in this paragraph. The instrument has a hand-held portion, a working portion, a plurality of actuators for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion, a plurality of sensors for sensing positions of the working portion relative to the hand-held portion, and a control system for controlling the instrument. The method comprises the steps of: manually grasping and moving the hand-held portion during the medical procedure to treat the tissue of a patient with the working portion; and operating the control system so that the control system establishes a home position of the working portion relative to the hand-held portion and tracks deviation of the working portion from the home position as the working portion moves in one or more of the plurality of degrees of freedom relative to the hand-held portion in order to maintain a desired relationship to a virtual boundary associated with the tissue during the medical procedure. The control system controls a cutting speed of the working portion based on the deviation.

The present invention also provides an instrument for treating tissue during a medical procedure, as described in this paragraph. The instrument comprises a hand-held portion for being manually supported and moved by a user. A drive assembly is movably coupled to the hand-held portion and supports a working portion. A plurality of actuators are operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion. A tracking device is mounted to the hand-held portion for tracking the instrument during the medical procedure. The drive assembly supports one of the actuators and is movable by at least another of the actuators in at least one degree of freedom relative to the hand-held portion.

The present invention also provides an instrument for treating tissue during a medical procedure, as described in this paragraph. The instrument comprises a hand-held portion for being manually supported and moved by a user. A working portion is movably coupled to the hand-held portion. A plurality of actuators are operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion. A tracking device is attached to the hand-held portion for tracking the instrument. At least adjustment one mechanism is disposed between the actuators and the working portion for transmitting movement from the actuators to the working portion.

The present invention also provides an instrument for treating tissue during a medical procedure, as described in this paragraph. The instrument comprises a hand-held portion for being manually supported and moved by a user. A working portion is movably coupled to the hand-held portion. A plurality of actuators are operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion. A tracking device is mounted to the hand-held portion for tracking the instrument during the medical procedure. A gimbal supports movement of the working portion in at least two of the degrees of freedom relative to the hand-held portion.

The present invention also provides an instrument for treating tissue during a medical procedure, as described in this paragraph. The instrument comprises a hand-held portion for being manually supported and moved by a user. A working portion is movably coupled to the hand-held portion. A plurality of actuators are operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion. A drive motor is supported by the hand-held portion and includes a drive shaft coupled to the working portion for rotating the working portion about a cutting axis. A tracking device is mounted to the hand-held portion for tracking the instrument during the medical procedure. One of the actuators includes a motor having a hollow rotor that rotatably receives the drive shaft therein such that the drive shaft of the drive motor rotates within the hollow rotor and relative to the hollow rotor so as to rotatably drive the working portion.

The present invention also provides an instrument for treating tissue during a medical procedure, as described in this paragraph. The instrument comprises a hand-held portion for being manually supported and moved by a user; a cutting accessory movably coupled to the hand-held portion; a plurality of actuators operatively coupled to the cutting accessory for moving the cutting accessory in a plurality of degrees of freedom relative to the hand-held portion, the plurality of actuators including an axial actuator for translating the cutting accessory along an axis; a drive motor including a drive shaft for rotating the cutting accessory about a cutting axis; a tracking device mounted to the hand-held portion for tracking the instrument during the medical procedure; and a collet assembly rotatably coupling the drive shaft to the cutting accessory so that the cutting accessory rotates about the cutting axis upon rotation of the drive shaft, the collet assembly configured to release the cutting accessory in response to actuation of the axial actuator beyond a predefined limit of actuation.

The present invention also provides an instrument for treating tissue during a medical procedure, as described in this paragraph. The instrument comprises a hand-held portion for being manually supported and moved by a user. A rotating cutting accessory is movably coupled to the hand-held portion. A plurality of actuators are operatively coupled to the cutting accessory for moving the rotating cutting accessory in a plurality of degrees of freedom relative to the hand-held portion. A tracking device is attached to the hand-held portion for tracking the instrument. A sleeve at least partially covers the cutting accessory and moves with the cutting accessory in each of the plurality of degrees of freedom. The cutting accessory is configured to rotate within the sleeve during the medical procedure.

The present invention also provides a system for treating tissue during a medical procedure. The system comprises an instrument adapted to be manually supported and moved by a user. The instrument includes a hand-held portion. The working portion is movably coupled to the hand-held portion. A plurality of actuators are operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion. A tracking device is attached to the hand-held portion for tracking the instrument. The system includes a navigation system for determining a position of the working portion relative to a virtual boundary associated with the tissue being treated. A control system is in communication with the actuators and is configured to control the actuators to actively position the working portion at the boundary while the user moves the hand-held portion relative to the boundary such that the working portion is substantially maintained at the boundary independent of the movement of the hand-held portion.

The present invention also provides a system for treating tissue during a medical procedure, as described in this paragraph. An instrument is adapted to be manually supported and moved by a user. The instrument includes a hand-held portion. A working portion is movably coupled to the hand-held portion. A plurality of actuators are operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion. A tracking device is attached to the hand-held portion for tracking the instrument. The system includes a navigation system for determining a position of the working portion relative to a target volume of the tissue to be removed. A control system is in communication with the actuators and is configured to control the actuators to move the working portion relative to the hand-held portion such that the working portion autonomously follows a path defined in the control system to remove the target volume of material while the user substantially maintains the hand-held portion in a gross position relative to the target volume during the medical procedure.

The present invention also provides a system for treating tissue during a medical procedure, as described in this paragraph. The system comprises an instrument adapted to be manually supported and moved by a user. The instrument includes a hand-held portion, a working portion movably coupled to the hand-held portion, a plurality of actuators operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion, and a tracking device attached to the hand-held portion for tracking the instrument. The system includes a navigation system for determining a position of the working portion relative to a virtual boundary associated with the tissue being treated. A display is in communication with the navigation system for indicating the position of the working portion relative to the virtual boundary. A control system is in communication with the actuators to control the actuators to move the working portion relative to the hand-held portion. The control system is configured to establish a home position of the working portion relative to the hand-held portion and track deviation of the working portion from the home position as the working portion moves in one or more of the plurality of degrees of freedom relative to the hand-held portion in order to maintain a desired relationship to the virtual boundary during the medical procedure. The display indicates the deviation of the working portion relative to the home position.

The present invention also provides a system for treating tissue during a medical procedure, as described in this paragraph. The system comprises an instrument adapted to be manually supported and moved by a user. The instrument includes a hand-held portion, a working portion movably coupled to the hand-held portion, a plurality of actuators operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion, and a tracking device attached to the hand-held portion for tracking the instrument. The system includes a navigation system for determining a position of the working portion relative to a virtual boundary associated with the tissue being treated. A display is in communication with the navigation system for indicating the position of the working portion relative to the virtual boundary. A control system is in communication with the actuators to control the actuators to move the working portion relative to the hand-held portion. The control system is configured to control the display to change a resolution of the display as the working portion approaches the virtual boundary.

The present invention also provides a method for performing a spinal fusion procedure on a patient's spine. The method comprises: establishing a virtual boundary associated with the patient's spine; providing access through skin to the patient's spine; manually holding an instrument having a hand-held portion, a cutting accessory, a plurality of actuators for moving the cutting accessory in a plurality of degrees of freedom relative to the hand-held portion, and a tracking device; operating a tracking and control system for the instrument to track movement of the cutting accessory relative to the virtual boundary; moving the cutting accessory through the incision in the skin; cutting away material from the patient's spine wherein the tracking and control system controls the actuators to move the cutting accessory relative to the hand-held portion so that the cutting accessory is substantially maintained in a desired relationship to the boundary during cutting; and fitting an implant into the patient's spine after cutting away material from the patient's spine.

The present invention also provides a method for performing a procedure on a patient's hip. The method comprises: establishing a virtual boundary associated with a femoral head of the patient wherein the virtual boundary defines a volume of material that creates a cam impingement between the femoral head and an acetabulum of the patient; providing access through skin to the femoral head of the patient; manually holding an instrument having a hand-held portion, a cutting accessory, a plurality of actuators for moving the cutting accessory in a plurality of degrees of freedom relative to the hand-held portion, and a tracking device; operating a tracking and control system for the instrument so that the tracking and control system tracks movement of the cutting accessory relative to the virtual boundary; moving the cutting accessory through the incision in the skin to the femoral head; and cutting away the volume of material from the femoral head that creates the cam impingement with the acetabulum to relieve the impingement. The tracking and control system controls the actuators to move the cutting accessory relative to the hand-held portion so that the cutting accessory is substantially maintained in a desired relationship to the virtual boundary during cutting to remove the defined volume of material.

The present invention also provides a method for performing a procedure on a patient's knee. The method comprises: establishing a virtual boundary associated with the femur and tibia of the patient wherein the virtual boundaries define a volume of material to be removed from the femur and tibia to receive a graft; creating an access path through skin of the patient to provide access to the femur or tibia of the patient; manually holding an instrument having a hand-held portion, a cutting accessory, a plurality of actuators for moving the cutting accessory in a plurality of degrees of freedom relative to the hand-held portion, and a tracking device; operating a tracking and control system for the instrument so that the tracking and control system tracks movement of the cutting accessory relative to the virtual boundaries; moving the cutting accessory through the access path to the femur or tibia; cutting away the volume of material from the femur and the tibia wherein the cutting occurs first through one or the femur or tibia to create a femur or tibia passage and with the cutting accessory positioned in the femur or tibia passage cutting then occurs in the other of the femur or tibia to form the other of the femur or tibia passage wherein the tracking and control system controls the actuators to move the cutting accessory relative to the hand-held portion so that the cutting accessory is substantially maintained in a desired relationship to the virtual boundaries during cutting in the tibia and the femur to remove the defined volume of material; and placing a graft in the tibia passage and the femur passage.

The present invention also provides a method for repairing a focal defect in cartilage of a patient. The method comprises: establishing a virtual boundary associated with the focal defect in the cartilage of the patient wherein the virtual boundary defines a volume of material to be removed around the focal defect; creating an access path through skin of the patient to provide access to the focal defect; manually holding an instrument having a hand-held portion, a cutting accessory, a plurality of actuators for moving the cutting accessory in a plurality of degrees of freedom relative to the hand-held portion, and a tracking device; operating a tracking and control system for the instrument so that the tracking and control system tracks movement of the cutting accessory relative to the virtual boundary; moving the cutting accessory through the access path to the focal defect; and cutting away the volume of material surrounding the focal defect. The control system controls the actuators to move the cutting accessory relative to the hand-held portion so that the cutting accessory is substantially maintained in a desired relationship to the virtual boundary during cutting to remove the defined volume of material.

The present invention also provides a method for preparing bone to receive an implant. The method comprises: establishing a virtual boundary associated with the bone of the patient wherein the virtual boundary defines a volume of bone to be removed to form an implant pocket shaped to receive an implant; providing access to the volume of bone to be removed; manually holding an instrument having a hand-held portion, a cutting accessory, a plurality of actuators for moving the cutting accessory in a plurality of degrees of freedom relative to the hand-held portion, and a tracking device; operating a tracking and control system for the instrument so that the tracking and control system tracks movement of the cutting accessory relative to the virtual boundary; moving the cutting accessory to the volume of bone to be removed; and cutting away the volume of bone to form the implant pocket. The tracking and control system controls the actuators to move the cutting accessory relative to the hand-held portion so that the cutting accessory is substantially maintained in a desired relationship to the virtual boundary during cutting so to remove the defined volume of bone. The method includes placing the implant in the implant pocket and securing the implant in position in the implant pocket.

Advantageously, the present invention provides for a compact design of the instrument, which beneficially allows the operator to easily manipulate the instrument, while actuators of the instrument position the working portion in a plurality of degrees of freedom relative to the hand-held portion. This compact design also reduces visual interference with the tissue being operated upon. The compact design allows for the hand-held portion to be sized and shaped to be held and supported in the hand of a user.

The present invention also advantageously provides feedback to the operator indicating relative position of the working portion of the instrument to the virtual boundary. The operator can determine the location of the working portion relative to the virtual boundary by observing deviation from the home position and/or speed attenuation of the working portion. The speed attenuation of the working portion can provide visual and/or aural indication of position of the working portion relative to the virtual boundary. Displays also provide feedback regarding the position of the working portion.

The control system provides the ability to operate the instrument in a variety of modes and to perform a variety of procedures. For example, the instrument can be operated in an active mode, a passive mode, or an autonomous mode. The control system, for example, controls the actuators to position the working portion in the plurality of degrees of freedom relative to the hand-held portion to maintain a desired relationship to the virtual boundaries.

The variety of procedures that can be performed with the instrument include, for example, sculpting, shaving, coring, boring, or any other method of removing tissue such as bone. The instrument can be used to remove tissue in spine, knee, hip, and other procedures. These procedures may be open procedures or minimally invasive procedures.

BRIEF DESCRIPTION OF THE DRAWINGS

Advantages of the present invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

FIG. **1** is a schematic view of a tracking and control system of the present invention;

FIG. **1**A is an illustration of a work boundary;

FIG. **2** is a perspective view of a surgical instrument used in the tracking and control system of FIG. **1**;

FIG. **2**A is a rear perspective view of the surgical instrument used in the tracking and control system of FIG. **1**;

FIGS. **3-5** are, respectively, front, top, and right views of the surgical instrument;

FIG. **6** is a top perspective view of the surgical instrument of FIG. **2** with protective covers, display, and covers removed;

FIG. **7** is a front view of the surgical instrument from FIG. **6**;

FIG. **8** is a cross-sectional view taken through the surgical instrument from FIG. **7**;

FIG. **9** is a top perspective view of an upper assembly of the surgical instrument of FIG. **6**;

FIG. **10** is a perspective view of the upper assembly;

FIGS. **11-15** are front, top, bottom, left-side, and right-side views of the upper assembly;

FIG. **16** is a cross-sectional view taken along the line **16-16** in FIG. **12**;

FIG. **17** is an exploded view of the upper assembly;

FIG. **17**A is a cross-sectional view of the upper assembly taken generally along the line **17**A-**17**A in FIG. **12**;

FIG. **17**B is a cross-sectional view of the upper assembly taken generally along the line **17**B-**17**B in FIG. **11**;

FIGS. **18-20** are back views of the upper assembly illustrating different pitch positions of an end effector of the upper assembly;

FIGS. **21-23** are top views of the upper assembly illustrating different yaw positions of the end effector;

FIGS. **24-27** are rear perspective views of the upper assembly illustrating different yaw/pitch positions of the end effector;

FIG. **28** is a top perspective view of a handle assembly of the surgical instrument of FIG. **6**;

FIG. **29** is a front and right perspective view of the handle assembly;

FIGS. **30-34** are front, top, bottom, left-side, and right-side views of the handle assembly;

FIG. **35** is a cross-sectional view taken along the line **35-35** in FIG. **31**;

FIG. **35**A is a cross-sectional view showing the sliding arrangement of the slider subassembly relative to the handle assembly;

FIG. **35**B is a partial rear perspective view of the instrument with a portion of the handle cut away to show a nut and lead screw;

FIG. **36** is an exploded view of the handle assembly;

FIGS. **37-39** are top views of the handle assembly illustrating different z-axis positions of a linear nut that drives the upper assembly;

FIG. **40** is a top perspective view of a slider subassembly of the upper assembly;

FIG. **41** is a rear perspective view of the slider subassembly;

FIG. **42** is an exploded view of the slider subassembly;

FIG. **43** is a bottom perspective view of the slider subassembly;

FIG. **43**A is a top view of the slider subassembly;

FIG. **44** is a cross-sectional view of the slider subassembly taken along the line **44-44** in FIG. **43**A;

FIG. **45** is a cross-sectional view of the slider subassembly taken along the line **45-45** in FIG. **43**A;

FIG. **46** is a top perspective view of the handle assembly with portions removed to illustrate a path for wires;

FIG. **47** is a top view of the handle assembly with portions removed;

FIG. **48** is a right view of the handle assembly with portions removed;

FIGS. **49** and **50** are perspective cross-sectional views taken along the lines **49-49** in FIG. **47** and illustrating additional paths for wires;

FIG. **51** is a perspective view of the handle assembly with a navigation bracket, drive enclosure, and wire sorter attached thereto;

FIG. **52** is a cross-sectional view taken along the line **52-52** in FIG. **51**;

FIG. **53** is an exploded view of the wire sorter;

FIG. **53**A is a perspective view of a ferrule;

FIG. **54** is an exploded view of the contents of the shell in which the motor controllers are housed;

FIG. **55** is an exploded view of the navigation bracket;

FIG. **56** is a top and front perspective view of the instrument illustrating the range of motion of the end effector;

FIG. **57** is a cross-sectional view of the end effector;

FIG. **58** is a flow chart showing the initialization steps of the system;

FIG. **59** is a flow chart showing the operational steps taken during use of the system;

FIG. **60** is a perspective view of a surface model of a work boundary;

FIG. **61** is a perspective view of a volume model of a work boundary;

FIG. **62** is an illustration showing a bur head outside of the work boundary;

FIG. **63** is an illustration showing the bur head at the work boundary;

FIG. **64** is a chart of a speed profile of the bur with respect to bur deflection;

FIG. **65** is an illustration of an application of the invention for use in bone sculpting;

FIG. **66** is an illustration of an application of the invention for use in bore tunneling;

FIGS. **67**A-**67**C are illustrations of an application of the invention for use in targeting/alignment;

FIG. **68** is an illustration of a potential display located on the instrument;

FIG. **69** is an illustration of an application of the invention for use in avoiding tissues or nerves;

FIG. **70** is an illustration of an application of the invention for use in depth control;

FIG. **71** is an illustration of an application of the invention for use in shaping implants;

FIG. **72** is a perspective view of a pencil-grip embodiment of the instrument including a proximal assembly and a distal assembly;

FIG. **73** is another perspective view of the instrument of FIG. **72**;

FIG. **74** is an exploded view of a portion of the instrument of FIG. **72**;

FIGS. **75**A-C are cross-sectional views of the instrument of FIG. **72** in various pitch positions;

FIG. **76** is a cross-sectional view of a portion of the instrument of FIG. **72**;

FIG. **77** is a cross-sectional view of another portion of the instrument of FIG. **72**;

FIG. **78** is a perspective view of a distal portion of the instrument of FIG. **72**;

FIG. **79** is an exploded view of the distal portion;

FIG. **80** is a perspective view of a nose tube;

FIG. **81** is a cross-sectional view of a collet assembly;

FIG. **82** is another cross-sectional view of the collet assembly;

FIG. **83** is an exploded view of the collet assembly;

FIG. **84** is a partially exploded view of a shaft between a collar and the collet assembly;

FIGS. **85-87** are cross-sectional views of the instrument in various positions along a z-axis;

FIG. **88** is a cross-sectional view of a portion of the instrument with the shaft positioned such that the cutting accessory can be removed upon further retraction of the nose tube;

FIG. **89** is a cross-sectional view of a portion of the instrument with the collet assembly in an unlocked position;

FIG. **90** is a cross-sectional view of the nose tube;

FIG. **91** is a perspective view of the lead screw

FIG. **92** is a cross-sectional view of the lead screw;

FIG. **93** is a cross-sectional view of an embodiment of the nose tube including an anti-backlash device;

FIG. **94** is another cross-sectional view of the anti-backlash device;

FIG. **95** is a cross-sectional view of a portion of the instrument of FIG. **72** including a gimbal;

FIG. **96** is a cross-sectional view of an adjustment assembly;

FIG. **97** is a perspective view of the adjustment assembly;

FIG. **98** is another perspective view of the adjustment assembly;

FIG. **99** is a cross-sectional view of the adjustment assembly;

FIG. **100** is another cross-sectional view of the adjustment assembly;

FIG. **101** is a perspective view of a portion of the adjustment assembly;

FIG. **102** is a perspective view of a carriage and a connecting member of the adjustment assembly;

FIG. **103** is a cross-sectional view of the carriage;

FIG. **104** is a perspective view of the connecting member;

FIG. **105** is another embodiment of the adjustment assembly including an anti-backlash device;

FIG. **106** is a perspective view of a portion of the adjustment assembly of FIG. **105**;

FIG. **107** is a view of a display screen including a target reticle, a depth legend, an extension extending from the depth legend, an acceptance circle, and an orientation legend;

FIG. **108** is a view of a display screen including a target reticle, a depth legend, an extension extending from the depth legend, an acceptance circle, an orientation legend, and a translation legend;

FIG. **109** is a view of a display screen including a target reticle, a depth legend, an extension extending from the depth legend, and an orientation legend;

FIG. **110** is a view of a display screen including a target reticle, a depth legend, an acceptance bar, and a translation legend;

FIG. **111** is a view of the display screen including a target reticle, a depth legend, and a translation legend;

FIGS. **112**A through **112**D illustrate steps of performing a surgical fusion;

FIGS. **113**A and **113**B illustrate steps of alleviating impingement between a femoral head and an acetabulum;

FIG. **114** illustrates an anterior cruciate ligament repair using a graft placed through passages formed in the femur and tibia;

FIGS. **115**A and **115**B illustrate steps of repairing a focal cartilage defect; and

FIG. **116** illustrates formation of a pocket in bone to receive a cranial implant.

DETAILED DESCRIPTION

I. Overview

Referring to FIG. **1**, a tracking and control system **100** is shown. Tracking and control system **100** tracks instrument **200** to keep a distal end tip **204** of a cutting accessory **202** that is attached to instrument **200** in a desired relationship to a predefined boundary. (Here “distal” means away from the practitioner holding the instrument **200** and towards the tissue to which the instrument is applied. “Proximal” means towards the practitioner and away from the tissue to which the instrument is applied.) The tracking and control system **100** controls the position of the cutting accessory tip **204** relative to a reference point on the instrument **200**. This control prevents the cutting accessory tip **204** from colliding with or breaching a boundary at the surgical site to which the cutting accessory **202** is applied.

Tracking and control system **100** can be used to keep the accessory distal end tip **204** outside of a predefined boundary. For example, it may be desirable to keep an active tip of an ablation instrument away from certain regions inside the body or away from certain body parts. It may also be desirable to control a depth of cutting. In this respect, the system **100** controls the position of the accessory distal end tip **204** to avoid those regions or body parts.

The depicted surgical instrument **200** is a motorized surgical handpiece. The instrument **200** includes a drive mechanism **201**, for example, referenced in FIGS. **8**, **16**, and **57**, coupled to a working portion, e.g., cutting accessory **202**. In some embodiments where the cutting accessory **202** rotates, e.g., a bur, a drill bit, etc., the drive mechanism **201** rotates the working portion about a rotational axis R. As set forth further below, with respect to the instrument **200**, the rotational axis R moves relative to a hand-held portion, e.g., handle assembly **500**, in pitch, yaw, and along an axis Z. The drive mechanism **201** includes a motor **206** and can include other bearings, rods, etc., to transfer rotation from the motor **206** to the working portion, i.e., cutting accessory **202**.

A coupling assembly **207**, seen in cross section in FIG. **16**, is located forward of motor **206**. Coupling assembly **207** releasably holds different cutting accessories **202** to the instrument **200**. The coupling assembly **207** also provides a mechanical linkage between the motor **206** and accessory **202** so the accessory **202** can be actuated by the motor **206**. The cutting accessory **202** is the component that performs a medical/surgical task on the tissue of a patient. The types of cutting accessories that can be driven by instrument **200** include, saw blades, shavers, drill bits and burs. In FIG. **1**, the depicted cutting accessory **202** is a bur that has at its distal end a spherical bur head **204** for removing bone.

With reference to FIGS. **16** and **17**, a sleeve **209**, also referred to as a nose tube, at least partially covers the cutting accessory **202**. Cutting accessory **202** moves with sleeve **209** as the cutting accessory **202** moves about a plurality of degrees of freedom, e.g., pitch, yaw, and translation along axis Z, as discussed further below. The axis Z is also referred to as a z-axis. The sleeve **209** remains stationary about rotational axis R, i.e., the cutting accessory **202** is configured to rotate within the sleeve **209** during the medical procedure.

Tracking and control system **100** can track and control other types of surgical instruments **200**. These instruments include powered surgical instruments that output energy other than mechanical energy such as: electrical energy; photonic energy (light); RF energy; thermal energy; and that vibrate (emit mechanical energy in the form of vibrations). A surgical instrument **200** of this invention may not even have a power emitting component. The instrument **200** may include as a cutting accessory **202**. Alternatively, the cutting accessory **202** may be manually actuated. Examples of manually actuated cutting accessories include forceps and snares.

The illustrated instrument in FIGS. **1** and **1**A with bur as the cutting accessory **202** is shown being used to shape a portion of a femur **102**. The instrument **200** can be used to remove other types of tissue, including soft tissue.

With continued reference to FIG. **1**, the embodiment shown, the femur **102** has a target volume **104** of material that is to be removed by the bur head **204**. The target volume **104** is defined by a boundary **106** called the work boundary. This work boundary **106** defines the surface of the bone that should remain after the procedure. System **100** tracks and controls instrument **200** to ensure that bur head **204** only removes the target volume **104** of material and does not extend beyond the work boundary **106**. It should be appreciated that the work boundary in other embodiments may be defined by any shape or size and may include 2-D or 3-D shapes, lines, trajectories, surfaces, linear paths, non-linear paths, volumes, planes, bore holes, contours, and the like. In some embodiments, the work boundary can define a 2-D or 3-D boundary across which the instrument should not cross. In other embodiments, the work boundary may define a line, path, trajectory or course along which the working portion of the instrument should travel. In these cases, the work boundary is also referred to as a work path, work trajectory or work course.

II. Tracking and Control System

Referring to FIG. **1**, the tracking and control system **100** includes a navigation unit **108**. The navigation unit **108** tracks the positions and orientations of the femur **102** and surgical instrument **200**. The navigation unit **108** includes a camera **110**. A navigation computer **112** receives and processes signals from the camera **110**. The camera **110** is connected to the navigation computer **112** by data connection **107**. Data connection **107** may be an IEEE 1394 interface, which is a serial bus interface standard for high-speed communications and isochronous real-time data transfer. Data connection **107** could also use a company specific protocol.

One camera **110** that can be incorporated into system **100** is the FlashPoint® 6000 Camera sold by Stryker Corporation of Kalamazoo, Mich. The camera **110** includes three separate high resolution CCD cameras (not shown). The CCD cameras detect infrared (IR) signals. Camera **110** is mounted to a stand (not shown) to position the camera **110** above the zone in which the procedure is to take place to provide the camera **110** with a field of view of the below discussed trackers **114** and **116** that, ideally, is free from obstructions. Trackers **114** and **116** are also referred to as tracking devices **114** and **116**, respectively.

The navigation computer **112** can be a personal computer such as a laptop computer. Navigation computer **112** has a display **113**, central processing unit (not shown), memory (not shown), and storage (not shown).

The navigation computer **112** is loaded with software. The software converts the signals received from the camera **110** into data representative of the position and orientation of the objects to which trackers **114** and **116** are attached. Also associated with the navigation computer **112** is a mouse or other suitable pointer-input device and keyboard.

The camera **110** communicates with the navigation computer **112** via data connection **107**. The navigation computer **112** initially sets up and registers the navigation unit **108**. The software provides a graphical user interface (GUI). The software also provides the geometry and positioning of the work boundary **106**. The navigation computer **112** interprets the data received from the camera **110** and generates corresponding position and orientation data that is transmitted to an instrument controller **120**.

With reference to FIG. **1**, for example, trackers **114** and **116** are affixed to the instrument **200** and the femur **102**, respectively. Specifically, the tracker **114**, i.e., the tracking device **114**, is attached to a hand-held portion of the instrument **200**, as discussed below, for tracking the instrument **200**. Each tracker **114** and **116** has a plurality of optical markers in the form of light emitting diodes, such as three LEDs (not shown), that transmit infrared light to the camera **110**. In some cases, the optical markers are three or more light reflectors (not shown) for use with a camera unit (not shown) that transmits light that reflects off the light reflectors. In other procedures, additional trackers may be affixed to other bones, tissue, or other parts of the body, tools, or equipment.

Based on the light captured signals forwarded from the camera **110**, the navigation computer **112** determines the position of each optical marker and thus the position and orientation of the objects to which they are attached relative to the camera **110**. An example of the camera **110**, navigation computer **112**, and trackers **114**, **116** are shown in U.S. Pat. No. 7,725,162 to Malackowski et al., hereby incorporated by reference, including the camera, navigation computer and trackers and associated methods of operation and use disclosed therein.

The instrument controller **120** is in communication with the navigation computer **112** via a data connection **121**. Data connection **121** may be an IEEE 1394 interface, which is a serial bus interface standard for high-speed communications and isochronous real-time data transfer. Data connection **121** could use a company specific protocol. It should be appreciated that in some versions of this invention navigation computer **112** and instrument controller **120** may be single unit. Instrument controller **120** communicates with the instrument **200** by a data connection **123**.

Based on the position and orientation data and other below described data, the instrument controller **120** determines the position and orientation of the cutting accessory **202** relative to the femur **102**. By extension, the instrument controller **120**, determines the relative location of the accessory tip such as the bur head **204** to the working boundary **106**. Based on this determination, the controller **120**, if necessary, repositions the cutting accessory and attenuates the speed of the instrument motor **206** as discussed further below. Instrument controller **120** typically performs these operations in a single control loop. In many versions of the invention, the controller **120** repeatedly executes these control loops at a frequency of at least 1 kHz. In some versions of the invention, controller **120** includes plural CPUs. Depending on the structure of the controller **120** these CPU's operate in series and/or parallel. In FIG. **1**, instrument controller **120** is represented as a personal computer.

System **100** further includes an instrument driver **130**. Instrument driver **130** provides power to instrument motor **206** to control the motor **206**. The power supply and control components internal to driver **130** may be similar those in the surgical instrument control console described in U.S. Pat. No. 7,422,582, CONTROL CONSOLE TO WHICH POWERED SURGICAL HANDPIECES ARE CONNECTED, THE CONSOLE CONFIGURED TO SIMULTANEOUSLY ENERGIZE MORE THAN ONE AND LESS THAT ALL OF THE HANDPIECES hereby incorporated by reference, including the power supply and control components of the control console disclosed therein and associated methods of operation and use. Instrument driver **130** is in communication with the instrument controller **120** via a data connection **131**. Data connection **131** may be an IEEE 1394 interface, which is a serial bus interface standard for high-speed communications and isochronous real-time data transfer. Data connection **131** could use a company specific protocol. It should be appreciated that in other embodiments the instrument driver **130** could be integrated into or part of the instrument controller **120**.

With reference to FIGS. **1-8**, for example, a manually actuated trigger **208** mounted to the instrument **200** is selectively depressed to regulate actuation of the instrument motor **206**. A sensor (not identified) disposed inside the instrument **200** generates a signal as a function of the extent to which the trigger **208** is actuated. The output signals from the sensor are forwarded by a data connection **133** to the instrument driver **130**. Based on the state of this sensor signal and other inputs described below, the instrument driver **130** applies energization signals to the instrument motor **206**.

Display **113** shows a virtual representation (or 3-D model) of the femur **102** and cutting accessory **202**. The representation of the femur **102** is based on preoperative images taken of the femur **102**. Such images are typically based on MRI or CT scans. Alternatively intraoperative images using a fluoroscope, low level x-ray or any similar device could also be used. These images are registered to the tracking device **116** for tracking purposes. Once registered, movement of the femur **102** results in corresponding movement of the images on the display **113**. This can also be displayed on the display **1402** (see below). Screen shots of display **1402** are shown in FIG. **68** and in FIGS. **107-111**. It should be appreciated that the various features shown on the screen shots in FIGS. **68** and **107-111** can be used in any combination.

The instrument **200** and the femur **102** are registered to the navigation unit **108** to ensure that the position and orientation data corresponds to their true relative positions within an acceptable level of accuracy.

The display **113** (and/or **1402**) also shows the work boundary **106** using color coding, or other visual method of distinguishing the target volume **104** of material to be removed from material that is to remain in the femur **102**.

Referring to FIG. **1**A, the instrument controller **120** defines a constraint boundary **111** that is located a predetermined distance from the work boundary **106** to define a buffer **105**. In one implementation of the system, the instrument controller **120** determines the position of the center of the bur head **204**, relative to the constraint boundary **111** to control the instrument **200**. The relative distance between the working boundary **106** and the constraint boundary **111** is a function, in part, of the geometry of the cutting accessory **202**. For example, if the cutting accessory **202** includes a spherical bur head **204**, the constraint boundary is one-half the diameter of the bur head **204**. Thus, when the centroid of the bur head **204** is on the constraint boundary **111**, the bur's outer cutting surface is at the work boundary **106**.

III. Surgical Instrument

A. Overview

Referring to FIG. **1**, surgical instrument **200** communicates with the instrument controller **120** via the data connection **123**. The data connection **123** provides the path for the input and output required to control the instrument **200** based on the position and orientation data generated by the navigation computer **112** and transmitted to the instrument controller **120**.

The instrument **200** includes a hand-held portion, e.g., a handle assembly **500** as discussed further below, and a working portion, e.g., the cutting accessory **202**. The working portion is movably coupled to the hand-held portion. The hand-held portion is manually supported and moved by a user during the medical procedure to treat the tissue of a patient with the working portion. The user operates the instrument **200** by grasping and supporting hand-held portion, and the instrument **200** is unsupported by other mechanical arms, frames, etc.

The instrument **200** has a plurality of actuators, e.g., motors **220**, **222** and **224**. The motors **220**, **222**, and **224** are coupled to the working portion, e.g., the cutting accessory **202**, for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion, e.g., the handle assembly **500**. Each motor **220**, **222** and, **224** is controlled by a separate controller **230**, **232**, **234**, respectively. Controllers **230**-**234** can be those provided by Technosoft U.S., Inc. of Canton, Mich., part number IBL2401-CAN. In some embodiments, the motors **220**, **222**, **224** can be controlled by a single controller. Controllers **230**, **232** and **234** are wired separately to the motors **220**, **222** and **224**, respectively to individually direct each motor to a given target position. In some versions of the invention, controllers **230**, **232** and **234** are proportional integral derivative controllers. The data connection **123** may be a CAN-bus interface between the instrument controller **120** and the controllers **230**, **232**, **234** or any other high speed interface. In other embodiments, the controllers **230**, **232**, **234** can be integrated with or form part of the instrument controller **120**.

A power source **140** provides, for example, 24 VDC power signals to the motors **220**, **222** and **224**. The 24 VDC signal is applied to the motors **220**, **222**, and **224** through the controllers **230**, **232** and **234**. Each controller **230**, **232** and **234** selectively provides the power signal to the complementary motor **220**, **222** and **224**, respectively, to selectively activate the motor. This selective activation of the motors **220**, **222** and **224** is what positions the cutting accessory **202**. Power source **140** also supplies power to the controllers **230**, **232** and **234** to energize the components internal to the controllers. It should be appreciated that the power source **140** can provide other types of power signals such as, for example, 12 VDC, 40 VDC, etc.

The motors **220**, **222**, **224** move the cutting accessory **202** and, by extension the bur head **204**, when the bur head **204** approaches, meets, or exceeds the constraint boundary **111**. For example, the instrument controller **120** may determine that the bur head **204** is crossing the constraint boundary **111** as the bur head **204** removes bone. In response, the instrument controller **120** transmits a signal to at least one of the controllers **230**, **232** or **234** that causes the deflection of the cutting accessory **202** that moves the bur head **204** away from the constraint boundary **111**.

In one version of the invention, motors **220**, **222** and **224** are brushless DC servomotors. One servomotor is available from MICROMO of Clearwater, Fla., Part No. 1628T024B K1155. Each servomotor includes three integrated linear Hall-effect sensors (not shown) that transmit signals back to the instrument controller **120**. The levels of these signals vary as a function of the rotational position of the associated motor rotor. These Hall-effect sensors output analog signals based on the sensed magnet fields from the rotor. In the above-described motor, the sensors are spaced 120° apart from each other around the rotor. A low voltage signal, typically, 5 VDC, for energizing the motor Hall effect sensors is supplied from the controller **230**, **232** or **234** associated with the motor **220**, **222** or **224** in which the Hall-effect sensors are located.

The output signals from the Hall-effect sensors internal to each motor **220**, **222** and **224** are applied to the associated controller **230**, **232** and **234**, respectively. Each controller **230**, **232** and **234**, monitors the received signals for changes in their levels. Based on these signals the controller **230**, **232** or **234** determines the rotor position. Here "rotor position" is understood to be the degrees of rotation of the rotor from an initial or home position. A motor rotor can undergo plural 360° rotations. A rotor position can therefore exceed 360°. Each motor controller **230**, **232** and **234** maintains a scalar value referred to as a "count" representative of rotor position from the home position. The motor rotors rotate in both clockwise and counterclockwise directions. Each time the signal levels of the plural analog signals undergo a defined state change, the controller **230**, **232** and **234** increments or decrements the count to indicate an arcuate change in rotor position. For every complete 360° rotation of the motor rotor, the associated motor controller **230**, **232** and **234** increments or decrements the value of the count by a fixed number of counts. In some versions of the invention, the count is incremented or decremented between 1500 and 2500 per 360° revolution of the rotor.

Internal to each controller **230**, **232** and **234** is a counter (not illustrated). The counter stores a value equal to the cumulative number of counts incremented or decremented by the controller **230**, **232** or **234**. The count value can be positive, zero or negative.

Referring to FIGS. **2** through **8**, various views of the surgical instrument **200** are shown. This includes views of the instrument **200** with protective covers **240***a*, **240***b* (FIGS. **2**-**5**) and without protective covers **240***a*, **240***b* (FIGS. **6**-**8**). The protective covers **240***a*, **240***b* are two halves of a housing for an upper assembly **300** of the instrument **200**. The upper assembly **300** includes a drive assembly **314** that drives the cutting accessory **202**. Covers **240***a*, **240***b* are placed on either side of the upper assembly **300** and fastened together by fasteners or the like. In other embodiments, the protective covers **240***a*, **240***b* may be replaced by a one-piece covering or housing (not shown).

In addition to the upper assembly **300**, the instrument **200** includes the handle assembly **500**, a shell **670**, and a bracket assembly **700**. The drive assembly **314** is coupled to the hand-held portion, e.g., handle assembly **500**. The drive assembly **314** is slidably coupled to the handle assembly **500**. Bracket assembly **700** and shell **670** are fixed to the handle assembly **500**. Cutting accessory **202** extends distally forward from upper assembly **300**. The handle assembly **500** includes a pistol-grip style handle **502** for being manually handled by a user and the trigger **208**. Other embodiments have alternative handles with differing grip styles, such as a pencil grip.

B. Upper Assembly

Referring to FIGS. **9-17**, **24** and **41**, various views of the upper assembly **300**, of the instrument **200** are shown. The upper assembly **300**, and more specifically the drive assembly **314**, supports the working portion, e.g., the cutting accessory **202**. As set forth further below, the upper assembly **300** and the cutting accessory **202** move relative to the hand-held portion, e.g., the handle assembly **500**, in a plurality of degrees of freedom.

The drive mechanism **201** moves in at least one degree of freedom relative to the hand-held portion, e.g., handle assembly **500**. Specifically, the drive motor **206** moves in at least two degrees of freedom relative to the hand-held portion and, more specifically, moves in at least three degrees of freedom relative to the hand-held portion. At least one of the actuators moves the drive mechanism **201** and the drive motor **206** in pitch, yaw, and translation along the axis Z relative to the hand-held portion. Specifically, the motors **220**, **222**, and **224** move the drive mechanism **201** and the drive motor **206** in pitch, yaw, and translation along the axis Z, respectively, relative to the hand-held portion.

As best shown in FIGS. **18-27** and **56**, the plurality of actuators, e.g., motors **220**, **222**, and **224**, are capable of moving the working portion relative to the hand-held portion in at least three degrees of freedom including pitch, yaw, and translation along the axis Z. These individual degrees of freedom are best shown in FIGS. **18-20** (pitch), FIGS. **21-23** (yaw), and FIGS. **37-39** (z-axis). FIGS. **24-27** show a sample of possible positions for pitch and yaw, and FIG. **56** shows the resulting range of motion when all three degrees of freedom are expressed. Further, in an embodiment where the working portion, i.e., the cutting accessory **202**, comprises a bur head **204**, the drive motor **206** moves in four degrees of freedom relative to the hand-held portion, i.e., the drive motor **206** rotates the bur head **204**.

The upper assembly **300** includes a carrier **302**, as identified in FIG. **17**, for example. Carrier **302** is slidably mounted to handle assembly **500**. The carrier **302** is in the form of a single piece metal structure that is often formed from aluminum. Carrier **302** is shaped to have a base **305** that is in the form of a rectangular frame. A riser **307**, also part of the carrier **302**, extends vertically upwardly from the proximal end of the base. Flanges **303** extend outwardly along the opposed outer side edges of the base **305**. The flanges **303** ride in channels **504** formed in handle assembly **500**. As seen in FIG. **43**, the carrier **302** is further formed to have an elongated slot **317** that extends upwardly from the downwardly directed face of carriage base **305**. Slot **317** is semi-circular in cross sectional shape and extends the length of the base **305**. Slot **317** is centered on the longitudinal axis that extends along the downwardly directed face of the slot base **305**.

With reference to FIG. **17**, a gimbal housing **306** is mounted to carrier base **305**. Gimbal housing **306** holds a gimbal **304** disposed around motor **206** to pivotally secure the motor **206** to the carrier **302**. Working portion, e.g., cutting accessory **202**, moves about gimbal **304** in at least two degrees of freedom relative to the hand-held portion, e.g., handle assembly **500**. Specifically, the working portion is adjustable in pitch and yaw about the gimbal **304**. The gimbal **304** is movable along the axis Z relative to the hand-held portion, e.g., handle assembly **500**.

Gimbal **304** is a ring shaped structure that has an outer shape of sphere the opposed ends of which have been removed. Gimbal **304** holds the cutting accessory **202** to the upper assembly **300** so the cutting accessory **202** is able to pivot around two axes. More particularly, motor **206** and coupling assembly **207** are the components of the instrument **200** securely attached to the gimbal **304**. Gimbal **304** is located around the center of gravity of a subassembly consisting of the cutting accessory **202**, motor **206** and coupling assembly **207**. This minimizes the mass moment of inertia of the sub assembly as it is pivoted and maximizes the angular acceleration for a given supplied torque.

With continued reference to FIG. **17**, the gimbal housing **306** includes an upper collar **308** and a lower collar **310**. Collars **308** and **310** are both generally U-shaped. Upper collar **308** is mounted to a lower collar **310** by fasteners **301**. Fasteners **309** mount the lower collar **310** to the carrier base **305**. The opposed inner faces of collars **308** and **310** have surfaces that conform to slice sections through a sphere. Gimbal **304** is sandwiched between the collars **308** and **310**. Gimbal housing **306** and gimbal **304** are collectively shaped to both prohibit lateral and longitudinal movement of the gimbal yet allow the pivoting of the motor **206** and cutting accessory **202** in two degrees of freedom relative to the longitudinal axis extending through the gimbal housing **306**.

A fastener **424** prevents rotation of the gimbal **304** relative to the gimbal housing **306** in the roll direction, around the longitudinal axis through the housing **306**. Fastener **424** has a distal protrusion, that when installed in the upper collar **308**, mates in a slot **425** in the gimbal **304**. The slot **425** extends longitudinally along the gimbal **304**. The seating of stem of the fastener **424** in slot **425** inhibits rotation of the gimbal **304** and, by extension the cutting accessory **202** while allowing pitch and yaw adjustment of the cutting accessory **202**.

With continued reference to FIG. **17**, upper assembly **300** includes a pitch adjustment mechanism **312** that sets the pitch of the cutting accessory **202**. Here the "pitch" is the up-down angular orientation of a longitudinal axis or rotational axis R of the cutting accessory **202** relative to a horizontal plane through the center of the gimbal housing **306**. A yaw adjustment mechanism **412** sets the yaw of the cutting accessory **202**. "Yaw" is the right-left angular orientation of the longitudinal or rotational axis of the cutting accessory **202** relative to a vertical plane through the center of the gimbal housing **306**. Pitch and yaw adjustment mechanisms **312** and **412**, respectively, are actuated to simultaneously adjust the pitch and yaw of the cutting accessory **202**. The pitch adjustment mechanism **312** and the yaw adjustment mechanism **412** are also capable of independent adjustment.

The pitch adjustment mechanism **312** includes a link **316**, sometimes called a swing arm, that is a three-sided structure. Link **316** includes a base **319** from which a pair of parallel arms **318** extends distally outwardly. Link **316** is positioned so that the base **319** is located proximal to the carrier riser **307** and the free ends of the arms **318** are disposed against opposed sides of the lower collar **310**. The outer end of each arm **318** has a bore **320** with a counterbore **321**. A flanged bearing **322** is seated in each bore **320** and counterbore **321**.

A screw **324** extends through each bearing **322**. The screw **324** has a head **326** that holds the flanged bearing **322** to the arm **318**. Each screw **324** also has a threaded shaft **328** that engages a corresponding threaded bore **330** formed in the adjacent side of the lower collar **310**. Link **316** pivots relative to the gimbal housing **306** about the axis through the coaxial screws **324**. This axis extends through the center of the gimbal **304**.

Link base **319** is formed to have an elongated slot **332**. Slot **332** receives a guide post **334** extending from a proximal end of motor **206**. The guide post **334** rides in the slot **332** when the yaw of the cutting accessory **202** is being adjusted. When the pitch is being adjusted, the guide post **334** is moved by the link **316** to place the bur head **204** in the desired pitch position. The slot **332** is dimensioned with a relatively tight tolerance to the guide post **334** across its width, while still allowing the guide post **334** to freely slide in the slot **332** as the yaw of the cutting accessory **202** is changed. In one version of the invention guide post **334** has a diameter of 0.4 cm and, the width across the slot **334** is approximately 0.01 to 0.05 mm wider. The length across the slot **334** is approximately 2.1 cm.

Pitch adjustment mechanism **312** includes a lead screw **336** that is driven by motor **220**. The lead screw **336** has opposed first and second stems, **338** and **340**, respectively, that are cylindrical in shape. Stems **338** and **340** are located on opposing sides of a screw body **339** formed with threading (threading not illustrated). Each screw stem **338** and **340** is seated in a separate bearing **342**. Bearing **342** are located in opposed coaxial bores **344**, **345** formed in the carrier **302**. One bore, bore **344**, is formed in a portion of the riser **307**. The second bore, bore **345**, is formed in the carrier base **305**. An end plug **346** is threaded into a matching internal thread **347** formed in the riser **307** around bore **344** to secure the bearings **342** and lead screw **336** to the carrier **302**.

A spur gear **348** is fit over the upper of the two screw stems, stem **338**. Set screws, (not identified) hold the spur gear **348** to the stem **338** so that the gear rotates in unison with the stem **338**. Spur gear **348** has teeth that mate with teeth on a spur gear **352**. Spur gear **352** is fixed to the output shaft **354** of the pitch motor **220** by set screws (not identified). FIG. **17**A shows a cross-section through the lead screw **336**. A mounting bracket **358** secures the motor **220** to the proximally directed face of the carrier riser **307** with fasteners **360**. Specifically, the carrier riser **307** is formed to have an arcuate recess **362** that extends inwardly from the proximally directed face of the riser **307**. Recess **362** is shaped to receive a section of the cylindrically shaped motor **220**. Mounting bracket **358** is arcuate in shape so as to seat around the portion of the motor **220** that extends outward of the carrier riser **307**.

Pitch adjustment mechanism **312** further includes a yoke assembly **364**. The yoke assembly **364** includes a rectangular bar **366**. Bar **366** is formed so as to have an elongated bore **372**, only the openings of which are seen, that extends longitudinally through the bar **366**. Threaded fasteners **374** secure bar **366** to the outer face of the arm **318** of link **316** adjacent lead screw **336**. While not illustrated, bar **366** may be formed with a rib that projects outwardly from the face of the bar **366** that is disposed against the adjacent arm **318**. The rib has a width thereacross less than the width of the bar **366**. The link arm **318** is formed with a groove having a width that allows the close seating of the rib. This rib-in-groove facilitates the securing of the bar **366** to the link. This rib also allows bore **372** to be positioned relatively close to the link arm **318**.

Yoke assembly **364** further includes a three sided yoke **368**. A rod **370** is integral with the yoke **368** and extends distally forward from the yoke **368**. The rod **370** is cylindrical in shape. The rod **370** is slidably disposed in the bore **372** internal to bar **366**. A nut **376** is pivotally mounted to the yoke **368**. Nut **376** is formed to have opposed trunnions **377**. Each trunnion **377** seats in a bearing assembly **379** mounted to a side section of the yoke **368** (see FIG. **17**A). The nut **376** has internal threads that mate with the lead screw **336**.

The cutting accessory **202** is pivoted up and down, along the Y-axis, by actuating motor **220**. The resultant rotation of motor output shaft **354** is transferred through gears **352** and **348** to cause a like rotation of lead screw **336**. Nut **376** is attached to yoke **368**. Yoke **368** is, through rod **370** attached to link **316**. As a consequence of the attachment of nut **376** to the link **316**, the nut **376** is blocked from rotation. Consequently, the rotation of lead screw **336** results in the movement of the nut **376** up or down the lead screw **336**. The displacement of the nut **376** results in a displacement of rod **370** that results in a like displacement of the link **316**. During this displacement, the yoke **368** pivots around nut trunnions **377**. Rod **370** freely slides in and out of bore **372** internal to plate **366**. As a consequence of the up/down displacement of the portion of the bracket adjacent shaft, link **316** pivots about the axis through bearings **322**. When the pitch adjuster **316** pivots, the guide post **334** is forced to undergo a like displacement. This displacement of the guide post forces the motor **206** and cutting accessory **202** to likewise pivot. It should be understood that the downward pivoting of link **316** and guide post **334** cause an upward pivoting of the bur head **204**.

Lead screw body **339** has fine pitch and lead angle to prevent backdriving (i.e. it is self-locking). As a result, a load placed on the bur head **204** does not back drive the motor **220**. In one embodiment, the lead screw body **339** has a diameter of 0.125 inches (0.318 cm) and has a lead of 0.024 inches/revolution (0.061 cm/revolution). One such lead screw is available from Haydon Kerk Motion Solutions, Inc. of Waterbury, Conn.

Magnets **380** are mounted in a pair of pockets (not identified) defined in an outside surface of one of the link arms **318**. A plate **384** is mounted to the arm **318** by fasteners (not identified) to hold the magnets **380** in the pockets. Magnets **380** are mounted to the arm **318** so that the North pole of the first magnet and the South pole of the second magnet are adjacent the plate **384**. The magnets **380** are used to establish the zeroed (or "home") position for the cutting accessory **202** on the X-axis.

Yaw adjustment mechanism **412** includes a link **416** similar in shape to link **316**. While not apparent from FIG. **17**, as seen in FIGS. **11** and **12**, link **416** is located distally forward of link **316**. Link **416** includes a base **419** from which a pair of parallel arms **418** extends distally forward. A first end of each arm **418** has a bore **420** with a counterbore **421**. A flanged bearing **422** is supported in each bore **420** and counterbore **421**. Fastener **424**, the fastener that seats in the flanged bearing **422**, has a head **426** that holds the flanged bearing **422** to the top located arm **418**. Fastener **424** also has a threaded shaft **428** that engages a corresponding threaded bore **430** formed in upper collar **308**. A fastener **425**, similar but not identical to fastener **424**, holds the bottom located arm against lower collar **310**. Fastener **425** extends into a bore formed in the lower collar **310** (bore not identified). Link **416** is able to freely pivot relative to the carrier **302** about an axis defined by the flanged bearings **422**. This axis extends through the center of the gimbal **304**.

An elongated slot **432** is formed in link base **419**. Slot **432** is centered on and extends along the longitudinal axis of link base **419**. Slot **432**, like the slot **332** integral with link **316**, receives the guide post **334** extending from the proximal end of motor **206**. Slot **432** has a length of approximately 2.0 cm. Slot **432** is slightly smaller in end-to-end length than slot **332** integral with link **316** because the pitch of link **416** is greater than the yaw of link **316**. Consequently to ensure the same up/down and right/left arc of the distal end of the cutting accessory **202**, the movement of post **334** to the left and right of link **416** should be less than the movement of the post **334** up and down relative to link **316**. The side-to-side width across slot **432** is approximately equal to the side-to-side width across slot **332**. Guide post **334** freely moves up and down in the slot **432** when the pitch of the cutting accessory **202** is adjusted. When cutting accessory **202** yaw is adjusted, the guide post **334** is moved by the yaw adjustment mechanism **412** to place the bur head **204** in the desired position. The slot **432** is dimensioned with a relatively tight tolerance to the guide post **334** across its width, while still allowing the guide post **334** to freely slide in the slot **432** as the pitch of the cutting accessory **202** is changed by the instrument controller **120**.

The yaw adjustment mechanism **412** includes a lead screw **436** that is rotated by the motor **222**. The lead screw **436** has opposing first and second stems, **438** and **440**, respectively. Stems **438** and **440** are cylindrical in shape. The lead screw **436** has a threaded portion **439** located between stems **438** and **440**. Stems **438** and **440** are rotatably supported by two bearings **442** (with bushings (not numbered) in between). The bearings **442** are located in opposing bores **444**, **445** formed in the carrier **302**. An end plug **446** is threaded into a matching internal thread **447** in the carrier **302** to secure the bearings **442** and lead screw **436** to the carrier **302**. The first stem **438** supports a spur gear **448** that is fixed to the screw **436** by set screws (not identified). The spur gear **448** has teeth that mate with teeth on a spur gear **452**. The spur gear **452** is fixed to an output shaft **454** of yaw motor **222** by set screws (not identified). FIG. **17**B shows a cross-section through lead screw **436**.

A mounting bracket **458** secures motor **222** to the carrier **302** with fasteners (not identified). In particular, the proximal end of the carrier base **305** is formed with an arcuate recess **462** for receiving a section of the cylindrically shaped motor **222**. Mounting bracket **458** has an arcuate shape to seat over the portion of the motor that extends beyond the carrier **302** to hold the motor **222** in position.

The yaw adjustment mechanism **412** further includes a yoke assembly **464** mounted to link **416**. Yoke assembly **464** includes a rectangularly shaped bar **466**. Bar **466** is formed to have a bore **472**, only the opening of which is seen, that extends longitudinally through the bar **466**. Bar **466** is secured to the outer face of the bottom of two arms **418** of link **416** by fasteners (not identified). The bar **466** is secured to the adjacent arm **418** so that the bore **472** is directed towards the arm **418**. Bar **466** may be identical to bar **366**. Accordingly, the adjacent link arm **418** may have a recess for receiving a rib integral with the bar **466**.

The yoke assembly **464** includes a three sided yoke **468**. A cylindrical rod **470**, integral with the yoke **468** extends distally forward of the yoke **468**. The rod **470** is slidably disposed in bore **472** between bar **466** and the adjacent link arm **418**.

A nut **476**, identical to nut **376**, is pivotally mounted to the yoke **468** by trunnions **477**. Each trunnion **477** is seated in a bearing assembly mounted to the side of yoke **468**. The nut **476** has internal threads that mate with threads on the lead screw **436**. The connection of nut **476** to link **416** by yoke **468** and rod **470** prevents the nut **476** from rotation. Consequently, the rotation of lead screw **436** results in the right/left movement of the nut **476** along the screw **436**. Yoke **468** and, by extension, rod **470**, move to the right/left with the movement of nut **476**. The rod **470**, being slidably coupled to the link **416** and bar **466**, causes the link **416** to engage in the like displacement. During the movement of these components it should be appreciated that the yoke **468** pivots around the trunnions **477** and the rod **470** slides in and out of the bore **472**. Since link **416** is pivotally mounted to the gimbal housing **306**, the right/left displacement of the link **416** pivots the link **416** about the axis through bearings **422**. This pivoting of the link **416** forces guide post **334** to engage in a like right/left movement. The displacement of the guide post **334** results in opposed left/right pivoting of the bur head **204**.

The lead screw threaded portion **439** and complementary yoke nut **476** have a fine pitch and lead angle to prevent backdriving (i.e. it is self-locking). As a result, a large load placed on the bur head **204** does not result in undesired back driving of the yaw motor **222**. In one embodiment of the invention, the lead screw **436** is identical to lead screw **336**.

Magnets **480** are mounted in a pair of pockets (not identified) defined in an outside surface of one of the arms **418**. A rectangular plate **484** is mounted to the arm **418** by a pair of fasteners (not identified). Plate **484** holds magnets **480** in the pockets. Magnets **480** are mounted to the arm **418** so that the north pole of one magnet **480** and the south pole of the second magnet **480** both face the plate **484**. The magnets **480** are used to establish the home position for the cutting accessory **202** along the Y-axis.

A bracket **488** is fixed to the carrier **302** with fasteners **490**. Bracket **488** is mounted to the top surface of the carrier base **305**. The center of bracket **488** is open. The bracket **488** is formed to have two pockets, pocket **394** and pocket **494**. Pocket **394** is located immediately above carrier base **305**. Pocket **494** is spaced further above the carrier base **305**. Upon assembly of surgical instrument **200**, motor **206** is seated in and extends through bracket **488**. The arms **318** and **418** of, respectively links **316** and **416**, are both located outside of bracket **488**. The link arm **318** that holds magnets **380** is located adjacent pocket **394**. The link arm **418** that holds magnets **480** is located adjacent pocket **494**. Hall-effect sensors **392** and **492** are mounted in pockets **394** and **494**, respectively. The signal from Hall-effect sensor **394** varies as a function of the proximity of magnets **380**. The signal from Hall-effect sensor **494** varies as a function of the proximity of magnets **490**.

The analog signals output by Hall-effect sensors **392** and **492** are applied to, respectively, motor controller **230** and motor controller **232**. Each motor controller **230** and **232** has an analogue to digital converter, (not illustrated) to which the associated analogue Hall sensor signal is applied. Motor controllers **230** and **232** forward the digitized representations of the signals from Hall-effect sensors **392** and **492**, respectively, to controller **120**.

FIGS. **18**-**27** show various pitch and yaw positions of the cutting accessory **202**. From these Figures it can be appreciated that lead screw **336** is parallel with motor **220**. Lead screw **436** is parallel with motor **222**. This arrangement of the components of instrument **220** minimizes the overall size of the instrument **200**.

C. Handle Assembly

Referring to FIGS. **28** through **37** the handle assembly **500** is now described. The handle assembly **500** slidably supports carrier **302**. The sliding movement of the carrier

302 results in the linear adjustment of the cutting accessory **202** along the longitudinal axis Z (also referred to as a z-axis) of the instrument **200**. Handle assembly **500** comprises the handle **502**, a trigger assembly **506**, and a linear adjustment mechanism **513**.

The handle **502** is hollow and defines a cavity **503** in which motor **224** is disposed. At a top of the handle **502** is a wall **510**. A hand-grip portion of the handle **502** descends downwardly from the wall **510**. Wall **510** is formed with an opening **505** (identified in FIG. **37**) that extends into cavity **503**. Handle **502** is further formed to have two steps **509** and **511** (seen best in FIG. **50**) that are located below opening **505** and that define portions of cavity **503**. Step **509**, the more proximal of the two steps, is closest to wall **510**. Step **511** extends distally forward from and is located below step **509**. A threaded bore **515** extends downwardly from the base of step **511**.

As shown in FIG. **34**, elongated rails **508** extend longitudinally along the opposed sides of the top of handle wall **510**. Each rail **508** is shaped to define a groove **512**. Handle **502** is formed so that grooves **512** face each other. Bearing strips or liners **514** fit inside the grooves **512**. The bearing strips **514** are channel-shaped to define the channels **504** to receive the corresponding carrier flanges **303**. The carrier flanges **303** are supported in the bearing liners **514** such that the weight of the carrier **302** is born by the bearing liners **514**. The bearing liners **514** are preferably formed of a low friction material to facilitate sliding of the carrier flanges **303** in the bearing liners **514**. Such materials may include high performance polymers such as Iglide® J from Igus, Inc. of East Providence, R.I. Screws **517** hold the bearing liners **514** in position by engaging flats in the liners **514** at the screw locations (not shown).

Carrier **300**, handle **502** and liners **514** are collectively designed so that while carrier flanges **303** are able to slide back and forth in the liners **514**, there is ideally no up/down or right/left movement of the carrier **300** relative to the handle **502**. Specifically the handle **502** and liners **514** are designed so that the outer diameter of the liners **514** is slightly less than the diameter of the rail grooves **512** in which the liners **514** are seated. In some versions of the invention, the diameter of rail grooves **512** is between approximately 0.02 to 0.12 mm more the diameter of liners **514**. Liners **514** have an outer diameter of approximately 4.78 mm. The distance between the opposed faces of the liners **514** against which the carrier flanges **303** seat is also slightly less than distance between the opposed outer faces of the flanges **303**. This difference may be between approximately 0.05 and 0.15 mm. These features collectively minimize the up/down and right/left play of the carrier flanges **303** in the liners **514**.

Handle **502** has two spaced apart coaxial sleeves **523**, identified in FIG. **36**, that are integral with and located above wall **510**. One sleeve **523** extends forward from the proximal end of the wall **510**. The second sleeve **523** extends proximally rearward from the distal end of the wall **510**. Each sleeve **523** is formed to have a bore **524**.

Referring to FIG. **36**, the linear adjustment mechanism **513** includes a lead screw **516** that is rotated by motor **224**. Screw **516** has opposing first and second stems **518** and **520**, respectively that are cylindrical in shape. Screw **516** has a threaded body **519** located between stems **518** and **520**. Bearings **522** rotatably hold lead screw **516** to sleeves **523**. Two bearings **522** are disposed over each screw stem section **518** and **520**. Each pair of bearings **522** is located in one of the sleeve bores **524**. End plugs **526** and **528** are threaded into internal threads in the bores **524** to secure the bearings **522** and lead screw **516** to the handle **502**. (Bore threading not illustrated) End plug **526** is disposed in the distal end of distal most sleeve **523**. End plug **528** is disposed in the proximal end of the proximal sleeve **523**.

Inside bearings **522**, bushings **530** and **532** are disposed about the screw stems **518** and **520**, respectively. Bushing **530** has an annular, outwardly extending flange **534** that abuts an end of the threaded body **519** of the lead screw **516**. Bushing **532** is integrally formed with a bevel gear **536** that is located on the proximal end of the bushing. The bevel gear **536** is fixed to the screw stem **520** by set screws (only one shown). The bevel gear **536** has teeth that mate with teeth on another complimentary bevel gear **540**. The complimentary bevel gear **540** is fixed to an output shaft **542** of motor **224** by set screws, (not identified). The bevel gears **536**, **540** are positioned such that their corresponding teeth mate to rotate lead screw **516** upon actuation of motor **224**.

A mounting bracket **546** secures the motor **224** in the handle **502** with fasteners **548**. In particular, the handle **502** has an arcuate recess **550** (as shown in FIG. **49**) in the cavity **503** for receiving a portion of the cylindrically shaped outer wall of the motor **224**. Mounting bracket **546** is arcuately shaped to seat over the portion of motor **224** that extends away from the adjacent internal surfaces of the handle **502**.

A nut **552** is disposed in carrier slot **317**, seen in FIG. **35**A. Nut **552** has a center cylindrical body (not identified) from which two wings **557** (identified in FIG. **38**) extend. The nut **552** is formed so that wings **557** have a coplanar face. A portion of this coplanar face extends across the body of the nut **552**. The nut **552** is positioned so that the wings **557** are disposed against the face of the carrier base **502** on the opposed sides of slot **317**. Fasteners **553** (FIG. **35**B) extend through openings in wings **557** and complementary openings in the carrier base **305** to hold the nut **552** to the carrier **302** (nut and carrier openings not identified). The nut **552** has internal threads that mate with threads on the lead screw **516**. Since nut **552** is firmly attached to the carrier **302** it should be appreciated that the nut **552** does not rotate. Consequently, the rotation of the lead screw **516** results in the movement of the nut **552** and, by extension, the carrier **302** and attached components, relative to handle **502**.

As the nut **552** travels along the lead screw **516**, the carrier flanges **303** are able to freely slide in the bearing liners **514**. The entire mass of the upper assembly **300** moves relative to the handle **502** during displacement of nut **552** along the lead screw **516**. The lead screw **516** has fine pitch and lead angle to prevent backdriving (i.e. it is self-locking). As a result, a large load placed on the bur head **204** will not result in undesired back driving of the axial motor **224**. In one embodiment, the lead screw **516** is of the same diameter as and has the same lead as screws **336** and **436**.

A magnet holder **560**, now described by reference to FIGS. **35** and **35**B, is disposed in handle cavity **503**. Magnet holder **560** is a single piece unit that includes a beam **559** and a foot **561** located below the beam. Foot **561** has a length relative to the beam **559** such that the proximal end of the foot **561** is located forward of the proximal end of the beam **559** and the distal end of the beam **559** is located rearward of the distal end of the beam **559**. A closed end bore **563** (one identified) extends through each end of beam **559**. Bores **563** open from the underside of beam **559** and have longitudinal axes that are perpendicular to the longitudinal axis of the beam **559**. When instrument **200** is assembled, the proximal end of magnet holder beam **559** seats on handle step **509**; foot **561** seats on step **511**. A fastener **565** extends through the beam **559** and step **511** into handle bore **515** to secure magnet holder **560** to the handle **502**. A magnet **556** is mounted in each holder bore **563**. Magnets **556** are mounted to holder **560** so that the north pole of one magnet **556** and the south pole of the second magnet **556** are both directed to the carriage **302**.

A plate **564** is fixed to the nut **552** with the same fasteners **553** that mount the nut **552** to the carrier **302**. Plate **564** is disposed against the common planar outer face of nut wings **557**. A Hall-effect sensor **566** is seated in a pocket **567** formed in plate **564**. Sensor **566** outputs a signal that is function of the proximity of the sensor **566** to magnetic fields generated by magnets **556**. The analog signal output by sensor **566** is applied to controller **234**. Controller **234** digitizes this signal and forwards the digitized signal to the instrument controller **120**.

The trigger assembly **506** includes the trigger **208**. The trigger **208** slides in a trigger housing **570**. The trigger housing **570** is mounted to the handle **502** with fasteners (not identified). The trigger **208** has a head (not identified) shaped to be pressed by a finger of the user. A stem **574** extends rearward from the trigger head.

Trigger stem **574** is located inside a bore **576** in a trigger shaft **578**. A set screw holds the stem **574** inside the trigger shaft **578**. The trigger shaft **578** has a generally cylindrical head **580** sized to slide within a larger bore **582** of a trigger housing **570**. The head **580** has a rib **584** at a top thereof. The rib **584** is formed on a flat of the head **580**. The rib **584** extends upwardly into a corresponding groove **588** defined inside the trigger housing **570** as an extension of the bore **582**. The rib **584** slides in the groove **588** to prevent rotation of the trigger shaft **578** relative to the trigger housing **570**.

A spring pin **594** is located in a cylindrically-shaped pocket **590** of the handle **502**. In particular, the spring pin **594** has a head **592** located in the pocket **590**. A pin shaft extends forward from the head **592** into a correspondingly shaped bore **598** in the trigger shaft **578**. A spring **600** is at least partially positioned in the bore **598**. The spring **600** is located between an internal end wall of the trigger shaft **578** and the head **592** of the spring pin **594**. The spring **600** biases the trigger shaft **578** away from the handle **502**.

The trigger shaft **578** further defines a magnet pocket on an underside thereof. A magnet **606** is secured in the magnet pocket preferably with adhesive. The trigger housing **570** also defines a sensor pocket opposite the groove **588**.

A Hall-effect sensor **610** is secured in the sensor pocket preferably with adhesive. The Hall-effect sensor **610** transmits a variable signal back to the instrument controller **120** based on the distance of the magnet **606** from the Hall-effect sensor **610**. Accordingly, the instrument controller **120** can determine the amount of depression of the trigger **208** by the user. The data connection **133** transmits not only power signals and control signals between the motor **206** and the instrument driver **130**, but also transmits signals from the Hall-effect sensor **610** to the instrument console **130**.

FIGS. **37**-**39** show various Z-axis positions of the nut **552** (and carrier **302**) along the axis Z with respect to the handle **502**.

D. Wire Fittings

As now described by reference to FIGS. **40** through **45**, carrier **302** includes a number of bores through which wires are routed. These wires (not illustrated) are the wires over which sensor signals are received from and power signals are applied to the various components mounted to the carrier **302**. Carrier base **305** defines a pair of longitudinal through bores **612**. Each through bore **612** is located above and inwardly of a separate one of the flanges **303**. A guide tube **614**, preferably formed of plastic, is located inside each through bore **612**. The lumen **615** internal to one tube **614** functions as for the conduit for the eight wires that extend to motor **220**. The lumen **615** through the second tube **614** functions as the lumen for the eight wires connected to motor **222**. During assembly, the guide tubes **614** are inserted into one end of the bores **612**. A plug tube **616** closes the opposed end of each bore **612**. Each guide tube **614** has a first end disposed in the associated bore **612** and a second end with a head **618** that abuts the proximally directed face of carrier base **305**. As seen in FIG. **44**, each guide tube **614** is shaped so that at the distal end, the end disposed in carrier bore **612** there is a foot **617**. The foot **617**, which has the same arcuate dimensions as the body of the tube **614** has a surface coincident with the inner surface of the body of the tube **614** (surface not identified). Extending distally forward from the end of the tube body, this foot surface curves downwardly.

Two holes **620** extend downwardly from the top face **311** of carrier base **305**. Holes **620** are oval in cross sectional shape. Each hole **620** is located inwardly of and does not intersect an adjacent bore **612**. Carrier base **305** is further formed to have two opposed pockets **636**. Each pocket **636** extends inwardly from a side face **313** of the carrier **302**. Each pocket **636** intersects one of the through bores **612** and the adjacent hole **620**. A plastic sleeve **622** is seated in each hole **620**. Each sleeve **622** has a tubular body **630** dimensioned to slip fit in the hole **620**. Sleeve body **630** has a through bore **632**. A flange **628** extends radially outwardly from the upper end of the body **630**. The flange **628** seats in a counterbore around hole **620** to hold the sleeve **622** flush with carrier base top face **311**. A plug **624** is seated in each pocket **636**. Each plug **624** is formed with a mid bore **634**. When a sleeve **622** and adjacent plug **624** are fitted to the carrier base **305** the plug midbore **634** is aligned with the sleeve bore **632**. A pair of sleeves **626** are also mounted to carrier **302**. Each sleeve **626** is seated in a bore (not identified) that extends upwardly from one of the bottom face surfaces **315** of the carrier **302**. Each sleeve **626** is adjacent and located inward of the associated carrier bore **620**. Each sleeve **626** is also positioned to intersect the associated bore **612**. The outer face of sleeve **626** is flush with the bottom face **315** of the carrier base **305**. Each sleeve **626** is formed to have a bottom bore **638** aligned with the top bore **632** and the mid bore **634**. The plugs **622**, **624**, **626** are held in position by adhesive and/or press fit. All of the plugs **622**, **624**, **626** are preferably made from plastic.

FIGS. **46**-**50** illustrate the void spaces internal to the handle **502** through which the wires are routed through the handle **502**. These void spaces include a pair of wire troughs **640**. Troughs **640** are parallel recesses that extend inwardly from wall **510** in the top of the handle **502**. Each trough **640** holds a bundle of wires that extend to the carrier **302** (wire bundles not illustrated). The wire bundles include the wires that extend to the instrument motor **206**, the motors **220** and **224** that pivot the cutting accessory **202** and the Hall effect sensors **392**, **492**, and **566**.

The wires that extend through to the carrier **302** as well as the wires associated with trigger **208** and motor **226**, extend through handle cavity **503**. A wire sorter **642**, now described with reference to FIGS. **52**, and **53**, disposed in the cavity **503** holds the wires static. Referring to FIG. **53**, the wire sorter **642** has a head **650** dimensioned to slip fit in the handle cavity **503**. Head **650** is disposed on a plane that is perpendicular to the longitudinal axis through the cavity **503**. A number of openings **644** extend top to bottom through the head **650**. Openings **644** function as conduits through which individual wires and wire bundles pass through the cavity **503**. A threaded retainer **648** and ferrule

646 are positioned in each opening **644**. Legs **652** extend downwardly from the head **650**. In the depicted version of the invention, in the plane perpendicular to the top-to-bottom axis through the head **650**, the head **650** is oval in shape. The legs **652** extend downwardly from the opposed parallel sides of the head **650**. A foot **654** extends outwardly from the free end of each of the legs **652**. Wire sorter feet **654** are adhesively secured to an inner step around the bottom end shell lid **674** (FIG. **54**) so as to set the position of the sorter head **650** in the handle cavity **503**.

Wire Sorter **642** provides strain relief for the wire bundles running through the handle **502**. The ferrules **646**, which are formed of plastic, hold the wire bundles in place. The ferrules **646**, best seen in FIG. **53**A, are compressed inside the sorter openings **644** via a tapered front and the thrust provided on the tapered front by the threaded retainers **648**. Each ferrule **646** is slotted along its entire length such that it compresses diametrically as the threaded retainer **648** forces the ferrule's tapered tip into its tapered hole. While not called out in drawings, the diameter of each ferrule **646** is proportional to the diameter of the opening in which the ferrule **646** is seated.

E. Shell

Referring to FIG. **54**, the shell **670** is mounted to a bottom of the handle **502**. The shell **670** houses the controllers **230**, **232**, **234**. Shell **670** includes a rectangular case **676** in which the controllers **230**, **232** and **234** are disposed. Case **676** is open at the top. A lid **674** is secured over the open top end of the case **676**. Lid **674** is mounted to the bottom of the handle **502** with fasteners **672**. Internal to the case are standoffs **675** that are post-like in shape. Controllers **230**, **232** and **234** are stacked one on top of the other in the case **676**. One set of standoffs **675** hold the bottommost controller away from the bottom of the case **676**. A second set of standoffs hold the middle controller away from the bottommost controller. A third set of standoffs **675** hold the topmost controller away from the middle controller. The wires from the motors **220**, **222**, **224** and Hall effect sensors **392**, **492**, **566** terminate at the controllers **230**, **232** and **234**.

In alternative embodiments, the controllers **230**, **232**, **234** are mounted in the control unit **120** and not on the instrument **200**. These embodiments of the invention do not include shell **670**.

F. Tracker Bracket

Referring to FIG. **55**, the bracket assembly **700** is mounted to the handle **502** to hold the tracking device **114** if needed. In alternative embodiments, the LEDs of the tracking device **114** are built into the instrument **200** eliminating the need for the bracket assembly **700**.

Bracket assembly **700** includes a generally U-shaped bracket **701**. Bracket **701** has a pair of parallel mounting arms **702** that extend downwardly from a web **704**. An end of each mounting arm **702** is aligned with the handle **502** by alignment pins **706**. Fasteners **708** hold the mounting arms **702** to the handle **502**. The tracking device **114** is designed to be fixed to the handle **502**.

Bracket web **704** is formed with a threaded bore **710**. A block **712** is disposed over web **704**. A threaded fastener **716** extends through a bore **713** in block **712** and into web bore **710**. Fastener **716** holds block **712** to bracket **701** so that the block **712** is able to rotate around the axis through web bore **710**. Fastener **716** is longer in length than block **712**. A washer **718** is located immediately below the head of fastener **716** (fastener head not identified). To lock block **712** in a fixed orientation, fastener **716** is tightened down so that the block **712** is clamped between bracket web **704** and washer **718**.

To adjust the orientation of block **712**, fastener **716** is loosened. A spring **720** extends around fastener **716** below washer **718**. The opposed end of the spring **720** seats against a step (not illustrated) internal to block **721** that is inside the block bore **713**. When fastener **716** is loosened to adjust the rotational orientation of block **712**, spring **720** is in a compressed state between washer **718** and the step internal to the block **712**. This compressive force inhibits the free rotation of block **712** when fastener **716** is loosened.

While not illustrated, in some versions of the invention, bracket web **704** is formed with arcuately spaced apart teeth that radiate outwardly from bore **710**. The adjacent bottom surface of the block **712** is formed with complementary teeth. As part of the position of setting the rotational position of the block **712**, the block **712** is set so that the block teeth are interleaved between the complementary teeth in the bracket web **704**. This tooth-against-tooth engagement serves to further prevent rotational movement of the block **712** when in the locked state.

A second block, block **722** is rotatably attached to block **712**. Block **722** is positioned to abut a side face, face **714** of block **712**. Block **722** is formed with a through bore **723** that extends axially through the block **722**. Block **712** is formed with a second bore, (not illustrated) that extends inwardly from the center of face **714**. This second bore is perpendicular to block bore **713**. A fastener **726**, similar if not identical to fastener **716** extends through block bore **723** and into the second bore of block **712**. Fastener **726** holds block **722** to block **712** so that block **722** can rotate around the fastener **716**. A washer **728** is located between the head of the fastener **726** and block **722**. The tightening of fastener **716** causes block **722** to be clamped between block **712** and washer **718**.

While not illustrated, blocks **712** and **722** are formed with complementary teeth. The teeth integral with block **712** extend radially outwardly from the bore formed in block face **714**. The teeth integral with block **722** are formed in the face of the block **722** that seats against block **712**. As part of the process of fixing the rotational orientation of block **722**, the block **722** is rotated so that the teeth integral with block **722** engage between the teeth formed in face **714** of block **712**. This tooth-between-tooth engagement further locks block **722** to block **712**.

A spring **730** is disposed around fastener **726**. Spring **730** from washer **728** extends into block bore **723**. Spring **730** seats against a step internal to block bore **723**. When fastener **726** is loosened, spring **730** imposes a force on block **722** that inhibits the free rotation of block **722**.

Block **722** is further formed with a second bore, bore **724**. Bore **724** extends through one of the side faces of the block **722** toward bore **723**. A fitting **732** is press fit into bore **724**. Fitting **732** is provided with features not relevant to the current invention that facilitate the removable attachment of a tracker to the fitting **732**.

Block **712** rotates around a longitudinal axis between bracket arms **702**. Block **722** rotates around an axis perpendicular to the axis around which block **712** rotates. Thus this arrangement allows the position of tracker attached to fitting **732** to be selectively positioned around two rotational degrees of freedom. This facilitates the ability to orient the tracker to ensure good line-of-sight with the camera **110** of the navigation unit **108**.

In the depicted version of the invention, one bracket arm **702** is provided with a threaded bore **730**. The second arm **702** is provided with a threaded bore **740**. Bores **730** and **740** are both designed to receive fastener **716**. While not illustrated, the bracket arms **702** are provided with teeth around bores **730** and **740** similar to the teeth provided around web bore **710**. Thus, these structural features make it possible to mount blocks **712** and **722** to either one of the bracket arms **702**. This makes it possible to mount the tracker to either of the bracket arms **702** if such positioning facilitates the optimal positioning and orienting of the tracker to ensure a line of sight relationship with the localizer.

IV. Registration, Calibration and Homing

Referring to FIG. **58**, the basic steps taken to prepare the system for operation are shown (the system is considered to be the tracking and control system **100** and instrument **200**). In a first step **800**, the system is powered up. The software application for operating the system is started in step **802**. In steps **804** and **806**, the trackers **114**, **116** and the pointer (not shown) are initialized and the trackers **116**, **114** are placed on the target bone (e.g., femur **102**) and the instrument **200**.

With the tracking device **116** mounted to the femur **102**, the femur **102** (and any other bone or tissue) is registered in step **808** using registration techniques known to those having ordinary skill in the art. This may require the user to touch certain surfaces or landmarks on the femur **102** with a tracked pointer device. In some embodiments this requires the user to touch several points on the surface of the femur **102** while pressing a select button on a pointer device. This "paints" the points on the surface in the system for matching with a preoperative or an intraoperative image of the femur **102**. The preoperative image or an intraoperative image of the femur **102** is loaded into the navigation computer. The tracked portion of the femur **102** is registered to the preoperative image. By extension, this allows the tracking and control system **100** to, as the femur **102** moves, present an image of the actual position and orientation of the bone based on the preoperative image on the display **113** (and/or display **1402**).

In step **810** the work boundary **106** is defined. Software running on instrument controller **120** generates an initial definition of the work boundary **106**. The user typically has the ability and option to adjust the placement of the work boundary **106** as may be necessary. In some embodiments, the work boundary **106** is defined before the operation such as after the preoperative image is taken and a 3-D model of the femur **102** or other tissue is generated, but before the patient is prepared for surgery. Thus, the work boundary **106** may be defined preoperatively or intraoperatively.

In the calibration procedure in step **812**, the orientation and location of the tracking device **114** is calibrated relative to the handle **502** by reference to the fixed and known locations of divots **507** (FIG. **3**). In the embodiments in which the tracking device **114** is integrated into the instrument **200**, then such calibration would be unnecessary since the relative locations of the LEDs or other transmitters are known.

The pointer device is used to register the target bone **102** to tracking device **116**.

Referring to FIGS. **56** and **58**, a homing procedure of step **814** establishes the home position for the accessory distal end bur head **204**, the distal end of the bur head. This process establishes the initial positions of the carriage **302** and links **316** and **416**. Initially in this process, the counters internal to the controllers **230**, **232** and **234** that store the cumulative counts representative of the angular positions of rotors internal to motors **220**, **222** and **224** are set to zero.

The process by which carriage **302** is set in the home position along the axis Z is described first. At a beginning step of this process, controller **120** directs motor controller **234** to actuate the associated motor **224**. First, motor **224** is actuated to rotate lead screw **519** so as to cause the forward, distal, displacement of carriage **302**. During this time period, motor controller **234** monitors the signals from the Hall-effect sensors internal to the motor **224**. The controller **234** maintains the count in the counter that is representative of the total degrees of rotation of output shaft **542**. In some constructions of the invention, each incremental count associated the rotation of the motor rotor that results in the distal displacement of the motor rotor is a positive incremental count. Each incremental count associated with the rotation of the rotor resulting in the proximal movement of the carriage is a negative incremental count. As a result of the displacement of the carriage **302**, sensor **566** is advanced towards the distal of the two magnets **556** mounted to the handle **502**. As a result of the movement of the sensor **566** towards the distal magnet **566**, the output signal from the sensor changes.

During this displacement of the carriage **302**, controller **234** forwards to controller **120** the digitized representation of the signal output by Hall-effect sensor **566**. Also forward from controller **234** to controller **120** during this process is the cumulative count data representative of the rotational position of the motor rotor.

Controller **120** compares the data from the counter integral with controller **234** to a first threshold value. This first threshold value is a signal level representative of the signal Hall-effect sensor **566** outputs when the sensor **566** is in a defined position along handle **502**. This position of the carriage **302** can be considered the distal homing position. When the signal from sensor **566** reaches this first threshold level, controller **120** directs controller **234** to terminate the application of energization signals to the motor **224**. This stops the distal advancement of the carriage **302**. Controller **120** stores the current cumulative count value from the counter.

Controller **120** then directs motor controller **234** to apply energization signals are then applied to motor **224** to cause the motor to displace carriage **302**, proximally. During this displacement of the carriage **302**, controller **234** generates negative incremental counts representative of the degrees through which the rotor is rotated. These negative counts, when applied to the counter, cause the cumulative count to decrease. The cumulative count stored in the counter may decrease to zero or to a negative number. During this displacement of the carriage **302**, motor controller **234** again forwards the digitized representations of the output signal from Hall-effect sensor **566** and the data in the counter to controller **120**.

The motor **224** is actuated so as to cause carriage **302** to move along handle **502** to a proximal homing position. As a consequence of the displacement of carriage **302**, the signal output by the Hall effect sensor **566** changes levels as it moves away from the distal magnet **556** and toward the proximal magnet **556**. Controller **120** compares the signal from Hall-effect sensor **566** to a second threshold level. This second threshold level is the level of the signal sensor **566** outputs when the carriage **302** is in the proximal homing position. When the signal comparison indicates that the carriage **302** is in the proximal homing position, controller **120** instructs controller **234** to terminate actuation of the motor **224**. At this time, controller **120** also stores the count data from the counter internal to the controller **234**.

At this time, the controller **120** has stored as data the cumulative counts representative of the angular position of the motor rotor needed to displace the carriage **302** first to the distal homing position and then to the proximal homing position. The absolute difference between these two counts is calculated. This difference is divided by two. This value represents the number of counts, through which the rotor integral with motor **234** must be cycled from its current position in order to center carriage **302** to the home position on handle **502**. For example, in this process, computer may receive indication that: when the carriage **302** was in the distal homing position, the count value was 250; and when in the proximal homing position, the count value was −148. The difference between these count values is 398. One half this difference is 199.

Once this displacement count is calculated, controller **120** adds the value to the current count value. In the present example −148+199=51. This number is referred to as a target position. During the homing process, this target position is a positive or negative number equal to the cumulative count representative of the angular position the rotor integral with motor **234** should rotate to cause the displacement of carriage **302** to the axis Z home position. Controller **120** forwards this target position to motor controller **120**. The motor controller **234** in turn, applies energization signals to the motor **224** so as to cause the rotor to rotate towards this count represented by the target position. During the resultant rotation of the motor rotor, the changing values of the motor Hall-effect sensors result in the output of counts that result in the incremental increase of the count value stored in the controller counter.

During this step, motor controller **234** compares the cumulative count stored in the counter to the count represented by the target position. When these two values are equal, controller **234** terminates the application of energization signals to motor **224**. It should be understood that this rotation of the motor rotor and, by extension, lead screw **516** results in the displacement of carriage nut **552** along the lead screw **516**. This movement of nut **552** is what moved the carriage **302** and the cutting accessory **202** to their home positions along the axis Z.

Motors **220** and **222** are actuated in a like manner to position the cutting accessory **202** in the home positions along the X- and Y-axes. Specifically, motor **220** is actuated to pivot link **316** between opposed upper and lower homing positions. During this process, the signal from Hall-effect sensor **392** varies as a result of the displacement of magnets **380**. The digitized representation of this Hall signal as well as the count value from controller **230** is output to controller **120**. The signal from Hall-effect sensor **392** is compared between two threshold signal levels to determine when the link **316** reaches the threshold positions. The differences in the cumulative counts from the motor rotor when the link **316** is in these two positions is determined. The difference in cumulative counts is divided in two. The resultant quotient is added to the current count value to produce a target position. This target position is a positive or negative number equal to a targeted cumulative count. This targeted cumulative count is proportional to the angular position to which the motor rotor needs to be rotated to in order cause the movement of link **316** to its home position.

The target position is output from controller **120** to controller **230**. Controller **230** applies energization signals to the motor **220** that results in the rotation of the motor rotor. This rotation of the rotor results in the count maintained by the counter internal to the controller **230** reaching the cumulative count of the target position. Once the controller **230** determines the cumulative count and equals the target position, the controller **230** terminates the application of energization signals to the motor **220**. The rotation of the lead screw **336** and resultant displacement of nut **376** cause link **316** to pivot to its home position. This pivoting of the link **316** to the home position, in turn, causes the like pivoting of the cutting accessory **202** to its home position along the X-axis.

To move cutting accessory **202** to its home position on the Y-axis, motor **222** is actuated to pivot link **416** between opposed right and left homing positions. During this process, the signal from Hall-effect sensor **492** varies as a function of the movement of magnets **480** to/from the sensor **492**. During this homing process, controller **232** provides controller **120** with: the digitized representation of the output signal from Hall-effect sensor **492**; and the count value maintained by the controller **232** as a result of the rotation of the motor rotor. By way of example, motor **222** is initially actuated to cause link **416** to pivot to first pivot to the left homing position. Controller **120** compares the signal from Hall-effect sensor **492** to a first threshold level. This comparison is performed to determine when link **416** reaches the left homing position. Motor **222** is then actuated to pivot the link **416** towards the right homing position. Controller **120** recognizes that the link **416** is in this second homing position when the signal from Hall-effect sensor **492** reaches a second threshold level.

Controller **120** then computes the difference in count values from when the link **416** was in the right and left homing positions. This difference in count values is divided by two. The resultant quotient is added to the present cumulative count. This sum is a count value representative of the angular position to which the rotor integral with motor **222** needs to rotated to center link **416** in its home position. This count value is added to the current count value associated with the rotor integral with motor **222**. Controller **120** outputs this target position to controller **232**.

In response to receipt of this target position, controller **232** applies energization signals to the motor **222** that result in the rotation of the rotor. More specifically, the rotor is rotated so that the Hall-effect sensors integral with motor **222** output counts that result in the incrementing or decrementing of the cumulative count to the target position. Once controller **232** determines that the cumulative count equals the target position, the computer terminates the application of energization signals to motor **222**. During this process, the rotation of the motor rotor and lead screw **436** resulted in the displacement of nut **476** and the pivoting of link **416**. The link **416** is pivoted to its home position which results in a like pivoting of the cutting accessory **202** to the cutting accessory home position along the Y-axis.

Each controller **230**, **232** and **234** informs controller **120** of when the count of the rotor associated with the controller reaches the target position. Controller **120** accepts these state data as an indication that the cutting accessory **202** is in the home position. Once the cutting accessory **202** is centered on the X-, Y- and Z-axes, controller **120** zeros out the counters internal to the motor controllers **230**, **232** and **234** that maintain the rotor count values.

Once the cutting accessory **202** is in the home position, a navigation pointer may be used to determine the location of the distal end of the cutting accessory **202**, bur head **204**. Thus, the system **100** knows the position of the bur head **204** in the home position and its relation to the position and orientation of the hand-held portion. Accordingly, when the hand-held portion is moved by the user and its position and orientation is tracked using tracker **114**, the system **100** also tracks the position of the bur head **204**. In other versions of the invention, as a result of prior calibration processes, the position of the distal end of the cutting accessory **202** relative to the instrument **200** is assumed to be known.

Once registration, calibration, and homing (if used) are complete, the navigation unit **108** is able to determine the spatial position of the bur head **204** with respect to the target bone **102** and the target volume **104**. The instrument **200** is ready for boundary constrained cutting of the target volume of material **104** in step **816**.

V. Instrument Control

After the homing process, control by controller **120** of the instrument **200** are based on (1) the position and orientation data from the navigation computer **112**; (2) the cumulative count data from controllers **230**, **232**, **234**; and three signals indicating the extent to which trigger **208** is actuated.

As represented by FIG. **56**, surgical instrument **200** is designed to allow the displacement of the cutting accessory **202** that results in the displacement of bur head **204** in each of the X- (pitch), Y- (yaw) and Z-axes by at least +/−0.2 inches (+/−0.508 cm). Said differently, the distal tip or bur head **204** of the working portion is capable of a total displacement of at least 0.4 inches (1.016 cm) in each of the plurality of degrees of freedom. In another embodiment, for example, the distal tip **204** of the working portion, e.g., the bur head **204**, is capable of a total displacement of at least 0.2 inches (0.508 cm), i.e., +/−0.1 inches (+/−0.254 cm) in each of the plurality of degrees of freedom. In other embodiments, for example, the distal tip of the working portion is capable of total displacement of at least 0.5 inches (1.27 cm), i.e., +/−0.25 inches (+/−0.635 cm); at least 1.0 inches (2.54 cm), i.e., +/−0.5 inches (+/−1.27 cm); at least 1.5 inches (3.81 cm), i.e., +/−0.75 inches (+/−1.905 cm); at least 2.0 inches (5.08 cm), i.e., +/−1.0 (+/−2.54 cm); at least 2.4 inches (6.096 cm), i.e., +/−1.2 inches (+/−3.048), or at least 3.0 inches (7.62 cm), i.e., +/−1.5 inches (+/−3.81), or more. In many versions of the invention, the displacement of the bur head **204** along the X axis is equal to the displacement along the Y axis which is equal to the displacement along the Z axis.

The normal operating position of the cutting accessory **202** is the home position. The range-of-motion data provided above is given with respect to the bur's center. In many versions of the invention, when the bur head **204** is in the home position, the bur head **204** is able to travel an equal distance, up/down, right/left, proximal/distal along axis, respectively the X-, Y- and Z axis. If the potential displacement of the bur head **204** is equal along each axis, the bur head **204**, when in the home position can be considered to be in the center of the sphere that represents the range of motion defined by the control system **100**. The outer perimeter of the sphere is the outer perimeter of the potential movement of the bur head **204** away from the home position. As discussed below instrument controller **120** moves the bur head **204** away from the constraint boundary **111** when the bur head **204** intersects or crosses the boundary **111**. This deflection could be along any one, two or three of the axes along which the cutting accessory **202** can be displaced.

Referring to FIG. **59**, a sample flow chart of steps taken by the instrument controller **120** to control the instrument **200** is shown. In step **900**, the latest positions of the target bone **102** and the instrument **200** are transmitted from the navigation computer **112** to the instrument controller **120** over the data connection **121**. Using these data, the instrument controller **120** determines the locations of the working boundary, the constraint boundary **111** and bur head **204** in free space, step **902**. As part of step **902**, the relative location of the bur head **204** to the constraint boundary **111** is also computed. In step **904** the instrument controller **120** updates the navigation GUI (display **113**) with the position of the bur head **204** relative to the tissue to which the bur head **204** is applied. An indication of the location of the working boundary **106** may also be presented.

Regardless of the location of the bur head **204** to the constraint boundary **111**, when the bur head **204** is pressed against tissue, the bur head **204** is exposed to the resistance of the tissue. This resistance is in opposition to the force the practitioner places on the bur head **204** as a result of the practitioner moving the instrument **200** forward. The resistance of the tissue essentially is a force imposed on the cutting accessory **202** in opposition to the forward force placed on the cutting accessory **202** by the practitioner. This force is significant when the tissue is a hard unyielding tissue such as bone.

As discussed above, lead screws **336**, **436** and **516** and complementary nuts **376**, **476**, and **552**, respectively, are finely threaded. This fine threading prevents the displacement of the associated nut **376**, **476** or **552** when force is placed on the nut that is parallel to the longitudinal axis of the lead screw. By way of example, if the bur head **204** is pressed against a bone face so that the longitudinal axis of the cutting accessory **202** is normal to the bone face, the resistance of the bone becomes a back force against the cutting accessory **202**. This back force is transferred through coupling assembly **207** and gimbal **304** to the carriage **302**. By extension, this back force attempts to push carriage nut **552** proximally rearwardly. However, the fine pitch engagement of nut **552** over lead screw **516** inhibits, locks out, this proximal displacement of nut **552**. This locking out of nut **552** from rearward movement results in a like locking out of rearward movement by carriage **302** and, therefore, the cutting accessory **202**. It should likewise be appreciated that this locking out of the movement of lead screw **516**, likewise inhibits back driving of the output shaft **542** or rotor of motor **224**.

Similarly, the fine pitch engagement of nut **376** over lead screw **336** locks out unintended displacement of cutting accessory **202** along the X-axis. The fine pitch engagement of nut **476** over lead screw **436** locks out unintended displacement of cutting accessory **202** along the Y-axis. Again this locking out of the lead screws **376** and **476** prevents the back driving of, respectively, motors **220** and **222**.

In step **906**, the relative location of the centroid of the bur head **204** to constraint boundary **111** is evaluated by the controller **120** to determine if action needs to be taken, i.e., moving the bur head **204**, changing the rotational speed of the bur head **204**, stopping the bur head **204**, etc. Display **1402** (see below) can also be updated by the instrument controller **120**.

As depicted by step **908**, instrument controller **120** sends instructional data packets to the motor controllers **230**, **232** and **234**. These instructional data packets include the target position for the rotor of the motor **220**, **222** and **224** with which the controller is associated. Here, each target position is positive or negative number representative of a targeted cumulative count for the associated motor rotor. This targeted cumulative count is proportional to a target angular position for the motor rotor from the home position for the rotor integral with the motor **220**, **222**, or **224** controlled by the controller.

Instrument controller **120** generates and sends these instructional data packets to each motor controller **230**, **232** or **234** at the rate one packet every 0.5 to 4 milliseconds. In many versions of the invention, each controller **230** and **232** and **234** receives an instruction packet at least once every 2 milliseconds.

As represented by step **910**, instrument controller **120** also selectively regulates the speed of the instrument based on the relative location of the bur head **204** to the constraint boundary **111**.

In step **912**, visual feedback is provided to surgeon by a display located on the instrument **200** and separately wired to the instrument controller **120** with data connection **1002** to transmit and receive data to and from the instrument controller **120**.

The steps are repeated at step **914**.

Referring to FIGS. **60** and **61**, the work boundary **106** can be modeled as surfaces (FIG. **60**) or volumes (FIG. **61**). When surfaces are used to model the work boundary **106**, the surfaces can be tessellated into triangles, quadrilaterals, NURBS, etc. On the other hand, when the work boundary **106** is modeled as volumes, the volumes can be represented by cubical voxels or other parallelepiped-shaped voxels.

Referring to FIGS. **62-63**, operation of the instrument **200** with respect to the work boundary **106** and constraint boundary **111** is shown. Here, surgical instrument **200** is operated in what is referred to as a passive mode. In the passive mode, system **100** monitors the position of the bur head **204** relative to the working boundary **106**. When the bur head **204** approaches or intersects this boundary **106** system **100** deflects the position of the cutting accessory **202** and/or attenuates the speed of the motor **206**.

In FIG. **62**, bur head **204** is spaced away from the constraint boundary **111**. At this time controller **120** maintains the bur head **204** in the home position. When the surgical instrument **200** is in this state, instrument controller **120** continually sends data packets indicating target positions of zero to the motor controllers **230**, **232** and **234**. Assuming the cutting accessory **202** is already in the home position, the current cumulative counts maintained by the controllers **230**, **232** and **234** are already zero. Given that the target positions equal the current zero value cumulative counts, controllers **230**, **232** and **234** do not actuate motors **220**, **222** and **224**, respectively. Cutting accessory **202** is thus held in the home position.

As the bur head **204** advances against the tissue, the head **204** eventually contacts the working boundary **106** as represented by FIG. **63**. Instrument controller **120**, through connection to the navigation system **108**, recognizes that the bur head **204** is in this position as a consequence of the determination that the centroid of the bur head **204** has intersected the constraint boundary **111**. As a consequence of the bur head **204** being in this position, the instrument controller **120** calculates a new position, a deflected position, for the bur head **204** that is normal to the constraint boundary **111**. This deflected position is spaced from the home position. Specifically, using algorithms and other processes, the instrument controller **120** calculates the deflected position for the bur head **204**. This deflected position is calculated with reference to the reference frame of the instrument **200**. This deflected position is quantified as a set of distances along the X-, Y- and Z-axes relative to the home position.

Instrument controller **120** then generates a set of target position counts to which the rotors integral to the motors **220**, **222** and **224** must rotate to reposition the cutting accessory **202** at the deflected position. The target motor rotor angular positions are determined based on the following relationships:

1) During the up/down and right/left pivoting of the cutting accessory **202**, the cutting accessory **202** functions as a lever pivoting about the center of gimbal **304**. One end of this lever is bur head **204**. The opposed end of this lever is the nut **376** or **476**. This is because the displacement of the nut **376** or **476** is responsible for, respectively, the up/down or right/left pivoting of the cutting accessory **202**. There is approximately a first order relationship between the extent to which each nut **376** and **476** needs to be displaced from the home position of the nut in order to pivot the bur head **204** in the X- or Y-axes from its home position. In order to displace the cutting accessory **202** along the axis Z, carriage **302** and by extension carriage nut **552** must be displaced forwardly or rearwardly by the same distance. Accordingly, there is a linear relationship between the displacement of nut **552** from its home position and the displacement of the bur head **204** along the axis Z. (As a consequence of the pivoting of the cutting accessory **202**, in either the X- or Y-axis, there is some displacement of the bur head **204** from the home position in the axis Z. This displacement is accounted for in the algorithms that are used to determine the individual X-, Y- and Z-axes displacements of the bur head **204** in order to position the bur head **204** in the deflected position)
2) There is a first order relationship between the degrees of rotation of each lead screw **336**, **436** and **516** the linear displacement of the nut, respectively, nuts **376**, **476**, and **552**, fitted to the lead screw.
3) There is a first order relationship between the degrees of rotation of the rotor of each motor **220**, **222** and **224**, and the lead screw, respectively, lead screw **336**, **436** and **516** and geared to the rotor.
4) There is first order relationship between the degrees through which the rotor of each motor **220**, **222** and **224** rotates and the cumulative count representative of that position that is maintained by the associated controller **230**, **232** and **234**, respectively.

Based on the above relationships, once controller **120** determines the deflected positions for the bur head **204** on the X-, Y- and Z-axes, the computer determines the target position for each motor rotor. Controller **120** transmits packets to the motor controllers **230**, **232** and **234** containing these target positions. Based on these targets position, each motor controller **230**, **232** and **234** applies the appropriate energization signals to the associated motor **220**, **222** and **224**, respectively. These energization signals cause the rotation of the rotor that results in the repositioning of the carriage **302**, link **316**, and link **416** that displaces the bur head **204** into the intended deflected position.

In terms of time, it typically takes approximately 40 ms to displace the bur head **204** from the home position that to a deflected position that is approximately 2 cm away from the home position. During this time period the practitioner is still applying a forward force on the handpiece **200**. Thus, often, rather than the bur head **204** being totally withdrawn away from the surface of the bone to which the bur head **204** is applied, the bur head **204** remains pressed against the bone. However, as a result of the deflection of the bur head **204**, the bur head **204** only minimally, if any, crosses the working boundary **106**. If the bur head **204** does cross the working boundary **106**, it only goes beyond the boundary **106** by a distance that is within acceptable tolerance levels for the shape to which the tissue is being formed. Instead, as a result of the deflection of the bur head **204** along a line perpendicular to the constraint boundary **111**, the bur head **204** remains in contact with bone at the working boundary

106. Thus, while the bur head **204** continues to remove tissue, the tissue removed is in the section of the bone from which the practitioner wants to remove tissue.

When the system **100** is operated in the passive mode, the application of energization signals to the motor **206** is jointly regulated by the controller **120** and instrument driver **130**. Initially, by setting controls on the instrument driver **130**, the surgeon establishes a maximum speed for the motor **206**. Throughout the time the system **100** operates in the passive mode, controller **120** sends instruction packets to the instrument driver **130**, the process of step **908**. These packets indicate the percentage of the surgeon-established maximum speed at which the motor **206** should run. As long as controller **120** determines there is no need to deflect the cutting accessory **202**, these instruction packets indicate that the motor should run at 100% of the established maximum speed.

As long as these instruction packets are received, whenever instrument driver **130** receives an indication there has been depression of the trigger **208**, the driver outputs energization signals to cause the motor **206** to run at the maximum speed. Instrument driver **130** takes this action even if the depression of the trigger is such that, if the system was operated in the below-discussed manual mode, the driver would output energization signals that would cause the motor **206** to run at a speed below the maximum speed.

In the version of the invention illustrated by FIG. **64**, controller **120** causes the speed of the motor **206** to be selectively attenuated as a function of the extent to which bur head **204** is deflected away from the home position, i.e., the control system **100** tracks deviation of the working portion from the home position during the medical procedure. Here, controller **120** does not generate instructions to attenuate the motor speed as long as the computer determines there is no need to deflect the bur head **204** from the home position. In other words, the working portion is capable of operating at the maximum cutting speed when the working portion is in the home position and the control system **100** attenuates the cutting speed of the working portion when the working portion deviates from the home position. Specifically, as discussed further below, when the working portion crosses a virtual boundary, e.g., work boundary **106** defined in control system **100**, the working portion deviates from the home position to deflect the working portion away from the virtual boundary. Said differently, the working portion deflects away from the work boundary **106** of the tissue to prevent removal of tissue beyond the work boundary **106**.

The control system **100** attenuates the cutting speed of the working portion based on this deviation. Speed control of the motor **206** is based on several factors including 1) the maximum speed set by the practitioner, 2) the depression of trigger **208** by the practitioner, 3) the percentage of total deflection, and 4) the shape of the speed profile, i.e., FIG. **64**. When it is necessary for the computer to determine a deflected position for the bur head **204**, controller **120** determines the percentage of the deflection of the bur head **204**. This deflection is based on a proportional comparison of the necessary diversion to the maximum possible diversion of the bur head **204**. In one version of the invention, the maximum possible diversion is the distance from the home position to the outer range of the total possible deflection of the cutting accessory **202**. Along any one of the individual X-, Y- and Z-axes, this distance may be less than the actual possible maximum diversion of the cutting accessory **202** along that axis.

As long as the calculated necessary diversions of the bur head **204** are below a set percentage of the maximum possible deflection, controller **120** continues to not generate any instructions to attenuate the motor speed. Once the calculated deflection of the bur head **204** is above a threshold percentage of the maximum deflection, controller **120** starts to attenuate motor speed. In the example of FIG. **64**, the threshold percentage is 40% of the maximum deflection. When the system **100** is in this state, controller **120** transmits instruction packets to driver **130** that indicate the motor **206** is to be driven at less than 100% of the established maximum speed. These instruction packets direct console **130** to cause energization signals to be applied to the motor **206** that result in the motor **206** running at a speed that is less than 100% of the user-set speed for the motor **206**. Controller **120** determines the percentage of the user-set speed the motor **206** should operate at as a function of the percentage of the calculated deflection of the bur head **204** relative to the maximum possible deflection. In the speed profile of FIG. **64**, when the calculated deflection reaches 90% of the maximum possible deflection, controller **120** instructs the console **130** to turn off the motor **206**. As the deflection increases from 40% to 90% of the maximum possible deflection, controller **120** sends instruction packets to the console **130** indicating that the motor speed should be decreased linearly from the 100% of the user-set speed to the motor off state.

In some versions of the invention console **130** asserts signals to the instrument motor **206** that results in the active braking, active deceleration of the motor **206** to the attenuated speed. This braking is the primary force that decelerates the cutting accessory **202**. A secondary force that decelerates the cutting accessory **202** is the resistance of the bur head **204** against the tissue being cut.

In one version of the invention, controller **120** sends instruction packets to console **130** indicating the extent to which the motor speed should be attenuated at a frequency of between 500 and 2,000 Hz. These instruction packets are sent even when the bur head **204** is in position in which it is not necessary to slow the speed of the motor **204**.

The disclosed navigation system that determines the relative position of the instrument **200** to the working boundary **106** is exemplary, not limiting. For example, some navigation systems have trackers that reflect light. Still other navigation systems include trackers with sensors that monitor light or electromagnetic fields emitted by fixed sources.

Controller **120** determines the relative position of the bur head **204** to the constraint boundary **111**. In one version of the invention, instrument controller **120** performs this evaluation at a frequency of 1000 Hz. Many navigation systems do not provide navigation data indicating the relative position of the instrument **200** to the bone to which the instrument is applied at this frequency. Controller **120**, compensates for the relative slow updating of data from the navigation system. One method of performing this compensation is to first use the data from the navigation system to determine the positions of the trackers. These positions are determined for at a number of times in order to determine averaged positions. Based on these averaged tracker positions, the relative position of the distal end of the cutting accessory **202** to the working boundary is determined. These averaging processes make it possible to generate averaged indications of the position of the cutting accessory **202** relative to the working boundary **106** at times between the times of actual tracker positions are measured.

Each time controller **120** makes the above evaluation, the evaluation is made based on the assumption that the bur head

204 is in the home position. Thus, in this evaluation, the fact that the bur head **204** may be actually be in a deflected position is disregarded. Instrument controller **120** determines, based on each of these evaluations, what, if any, the appropriate deflected position is for the bur head **204**. Thus, if, as a result of one these evaluations, it is determined that the bur head **204** has crossed the constraint boundary **111**, controller **120** may determine that the deflected position for the bur head **204** is even further spaced from the home position than the current deflected position. Alternatively, instrument controller **120** may determine that, owing to the current relative position of the bur head **204** to the constraint boundary **111**, the appropriate deflected position for the bur head **204** is closer to the home position than the current deflected position. At the end of either determination, controller **120** generates target positions for the rotors integral to motors **220**, **222** and **224**. These target positions are transmitted to the motor controllers **230**, **232**, **234**. If the new target positions are different from the previous target positions, motor controllers **230**, **232**, **234** apply energization signals to the motors **220**, **222**, and **224**, respectively, in order to force displacement of the bur head **204** to the newly-determined target position.

As mentioned above, once instrument controller **120** determines it is appropriate to reposition the bur head **204** in a deflected position that is a defined distance away from the home position, the controller causes the speed of the motor **206** to be attenuated. As a consequence the drop off of motor speed, the pitch of the noises generated by the instrument **200** changes. One reason is that the fall off in motor speed invariably results in a change of characteristics of the noise emitted by the motor **206**. Should the bur head **204** be pressed against the bone, the pitch of the noise generated as a consequence of this metal-against-bone contact also changes. These changes in sound provide the practitioner feedback that the bur head **204** is approaching or at the working boundary **106**.

The above aural feedback the practitioner receives from the motor **206** is the reason in one embodiment system **100** is configured so that the user may not attenuate the motor **206** from the initially set maximum speed. If the practitioner is, during the procedure, allowed to so reduce the speed of the motor **206**, it may be difficult for the practitioner to aurally perceive an attenuation in motor speed as a consequence of the cutting accessory **202** approaching or breaching the working boundary **106**.

Another source of feedback to the practitioner is that, as a result of the slowing of the instrument the vibration of the instrument in the practitioner's hand changes. As a result of this feedback, the practitioner is placed on notice that, to avoid having the bur head **204** remove tissue beyond the working boundary **106**, it is necessary to reposition the bur head **204** and/or adjust the force applied to the instrument to press the bur head **204** against the bone.

Another feedback source the practitioner has regarding the position of the bur head **204** relative to the working boundary **106** is the relative position of the cutting accessory **202** to the rest of the handpiece. Visually moderate to large displacement of the cutting accessory **202** from the home position is readily apparent. The movement of the cutting accessory **202** to one of these displaced positions therefore serves as a visual cue to the practitioner that the bur head **204** is at or approaching the working boundary **106**.

There may be circumstances in which it appears that the position of the instrument is not being reset sufficiently to avoid having the bur head **204** remove tissue from beyond the working boundary **106**. It should be understood that when the instrument is in this position, it is already in the state in which the cutting accessory **202** is deflected from the home position. In this state though, the diversion of the cutting accessory **202** is less than the maximum possible diversion. In this case, the further necessary diversion of the cutting accessory **202** would exceed the maximum allowed diversion. In the example depicted in FIG. **64**, the maximum allowed diversion is 90% of the total diversion. If controller **120** determines it is necessary to so reposition the bur head **204** in order to avoid having the bur head **204** move beyond the working boundary **106**, the controller **120** sends an instructional packet to console **130** directing the console **130** to terminate the application of energization signals to the motor **206**.

The stopping of the instrument motor **206** has two end effects. First, the stopping of the motor **206** prevents the bur head **204** from cutting tissue beyond the working boundary **106**. Secondly, the stopping of the motor **206** provides the practitioner notice that, to avoid, cutting tissue outside of the working boundary **106**, it is necessary to reposition the instrument **200**. Repositioning of the instrument **200** away from the working boundary **106** results in the continued application of energization signals to the motor **206**.

After the bur head **204** is deflected, the practitioner continues to reposition the surgical instrument. As a consequence of this repositioning, controller **120** often determines that the instrument is positioned so that, if the bur head **204** is in the home position, the bur head **204** will be spaced from the constraint boundary **111**. When this condition occurs, controller **120** sends instruction packets to the motor controllers **230**, **232** and **234**, with target positions that indicate that the motor rotors should be in the home angular positions. The count values in these instruction packets are zero. In response to the receipt of these instruction packets, the motor controllers **230**, **232** and **234** selectively actuate motors **220**, **222** and **224**, respectively. The motors **220**, **222**, and **224** are actuated to return carriage **302** and links **316** and **416** back to their home positions. This displacement of the carriage **302** and the links **316** and **416** results in a like return of the bur head **204** to the home position.

System **100** can also control the position of the cutting accessory **202** in what is referred to as an "active" mode. In the active mode, controller **120** does not deflect the cutting accessory **202** away from a constraint boundary **111**. Instead, the controller **120** actively directs the cutting accessory **202** to a path along which tissue is to be removed. For example, the system may be operated in the active mode to cut a bore or other void space in the bone that is located along a specific longitudinal axis.

To form a void space in the active mode, the longitudinal axis of the void space is initially defined and loaded into the controller **120**. An extension of this axis is plotted to extend out of the bone. The practitioner, holding the instrument so that the bur head **204** is just above the location for the opening into the void space, brings the instrument into approximate alignment with this axis. This task is performed by reference to the image presented on the surgical navigation display. This image includes a depiction of the axis along which the void space is to be formed.

Initially, the controller **120** determines if the distal end of the cutting accessory **202** is within a set space above the surface of the bone in which the opening is to be cut. In some applications of this invention, this distance is approximately 0.5 to 1.5 cm. Controller **120** then determines if the cutting accessory **202** is within a given radius, a snapping radius of the location where the void is to be formed. This radius is typically less than the maximum deflection radius of the cutting accessory **202**. If the instrument **200** is not so positioned, the controller **120** causes a message to be presented on the navigation display that it is necessary for the practitioner to reposition the instrument. If controller **120** determines that the cutting accessory **202** is within the snapping radius, the computer deflects, snaps, the cutting accessory **202**. Specifically, controller **120** instructs the motor controllers **230**, **232**, **234** to actuate the instrument motors **220**, **222** and **224**, so that the distal end of the cutting accessory **202** is positioned immediately above the location at which the void space is to be formed. During these steps of the process, controller **120** sends instruction packets to console **130** that prevent the operation of the instrument motor **206**.

The practitioner's continued movement of the instrument thus results in the distal end of the cutting accessory **202** being pressed against the surface of the tissue at the location in which the void is to be formed. Again, at this time, the practitioner is not able to actuate the instrument motor **206**. Also, images are presented on the navigation display that indicate the relative location of the instrument to the axis along which the void space is to be formed.

Once the instrument **200** is so positioned, the practitioner, based on the images of the instrument relative to the target axis, orientates the instrument. As a consequence of the initial orienting of the instrument, controller **120** returns cutting accessory **202** to the home position. The practitioner continues to orient the instrument. Specifically, based on the images indicating the orientation of the cutting accessory **202** relative to the target axis, continues to orient the accessory until it is in registration over this axis.

As a consequence of the monitoring of the information on the navigation screen, the practitioner becomes aware of the fact that the cutting accessory **202** is aligned on the axis along which the void space is to be formed. Once the controller **120** determines that the instrument **120** is in this state, the controller starts to send instruction packets to console **130** indicating that the instrument motor **206** can be actuated. The practitioner at this time depresses trigger **208** to actuate motor **206**. The cutting accessory **202** is therefore energized so as to cause the formation in the tissue of the intended void space at both the target location and along the target axis.

Once the practitioner starts to form the void, controller **120** appreciably restricts the practitioner's ability to apply the cutting accessory **202** off the target axis. For example, in some implementations of the invention, as soon as the navigation system provides any indication that the cutting accessory **202** is moving off axis, controller **120** immediately instructs the console **130** to terminate the application of energization signals to the instrument motor **206**. Controller **120** takes this action without performing any deflection of the cutting accessory **202**. This reduces the likelihood that, as the depth of the void space increases, the void space is formed along an axis that is off axis with the target axis. In some implementations of this feature of the invention, the acceptable variation of the misalignment of the cutting accessory **202** with the target axis may vary inversely as the depth of the void space being formed increases.

Controller **120** monitors the depth of the cut. In some versions of the invention, when it is determined that that the depth of the void space is between 0.1 and 2.0 mm of the target depth, controller **120** starts to deflect the cutting accessory **202**. This particular type of deflection may just be the rearward retraction of the cutting accessory **202**. As the carrier is deflected, controller **120** sends instruction packets to console **130** that causes for the slowing and then the stopping of motor **206**. These process steps thus cause the resultant void space to be formed to the target depth.

In an alternative use of system **100** in the active mode, the system **100** displays prompts that direct the practitioner to position the handpiece so that bur head **204** is adjacent the surface of the tissue to be removed. This distance is less than maximum distance the bur head **204** can be deflected to from the home position. Typically, this distance is less than 20 to 80% of the total distance which the bur head **204** can be deflected.

Once the instrument **200** is so positioned, the instrument controller **120** sends instructions to the motor controllers **230**, **232** and **234** that result in the diversion of the bur head **204** from the home position towards the tissue that is to be cut. The bur head **204** removes the tissue. During this process, the instructions controller **120** generates instructions regarding the displacement of the bur head **204**, only result in the displacement of the bur head **204** towards the working boundary **106**. Controller **120** does not send instructions that would result in the repositioning of the bur head **204** beyond the working boundary **106**. Thus, in this process, the controller **120** sends the instructions that direct the bur head **204** to sculpt the bone into the desired shape.

In this process, the practitioner may move the instrument closer towards the bone being cut. In response to the controller **120** determining that the instrument is being so repositioned, the computer adjusts the extent to which the bur head **204** needs to be deflected to perform the desired tissue removal. In this readjustment of the position of the bur head **204**, the bur head **204** may be reset to the home position. In situations where the instrument **200** is moved even closer to bone, controller **120** may then determine it is necessary to start deflecting the bur head **204** away the tissue being cut. Thus, an aspect of this active mode operation of the instrument may include the passive mode diversion of the bur head **24** in order to avoid removing tissue beyond the working boundary.

The above described operation of the system **100** alternating between the active and passive modes can be considered a hybrid mode operation of the system **100**. The operation may be useful to form surfaces of the bone. These surfaces include surfaces located inwardly from the exposed face of the bone that define void spaces located within the bone.

The system **100** can also be operated in a manual override mode. In this mode the user overrides the ability of the motors **220**, **222**, **224** to re-position the bur head **204**. In this mode the instrument **200** defaults to the home position and essentially become a fixed, stiff, burring tool. Elements of controlling the rotational speed of the burhead **204** could be maintained if desired (for example: cutting outside of the constraint boundary **111** could still be disallowed). A complete override would allow the user to use the trigger **208** to vary the rotational speed of the bur head **204** (in the active and passive modes, the trigger **208** is simply an on/off safety feature). This would essentially make the instrument **200** a conventional instrument because it would no longer be guided by the navigation unit **108**.

It should be understood that when the instrument is operated in the above-described modes, the self locking features of the nuts on the lead screws prevent the unintended displacement, backdriving, of the bur head **204** from the home position.

The passive and active modes can be thought of as the two ends of a spectrum of possible operating modes (for surface machining), but variants are possible. For instance, the system **100** could operate in a passive mode with bur tip prediction. In this mode, the bur head **204** starts accelerating away from the work boundary **106** prior to actually reaching the work boundary **106**. To do this, estimates of future positions of the bur head **204** are needed. In addition to positions, the speeds of both the target bone **102** and instrument **200** are outputted from the navigation unit **108** to the instrument controller **120** to predict the future positions of the bur head **204** relative to the bone **102** and instrument **200** and react accordingly. This mode utilizes knowledge of each motor's performance specifications (akin to knowing a motor's speed-torque curve). This variant of the passive mode increases the instrument's performance envelope (reactivity) and overall accuracy.

Another hybrid mode is adding a longer "sticking" time. In such a mode, the control system **100** is configured to control the actuators, e.g., motors **220**, **222**, and **224**, to actively position the working portion at the boundary while the user moves the hand-held portion relative to the boundary such that the working portion is substantially maintained at the boundary independent of the movement of the hand-held portion. In essence, the bur head **204** acts like a magnet to a boundary only after the bur head **204** has begun "riding" on that boundary. This is accomplished by allowing the bur head **204** to travel beyond the "Home" position while the bur head **204** is pulled away from the boundary. This feature may be adjustable as a user preference.

Still another hybrid mode of operation is semi-autonomous cutting. In this mode, the control system **100** is configured to control the actuators to move the working portion relative to the hand-held portion such that the working portion autonomously follows a path defined in the control system **100** to remove the target volume of the material while the user substantially maintains the hand-held portion in a gross position relative to the target volume during the medical procedure. Here, the user grossly positions the bur head **204** and then holds the instrument **200** in a region of interest. The bur head **204** is then guided and moved based on signals from the instrument controller **120** to the controllers **230**, **232**, **234** to cut out the target volume of material **104** defined by the work boundary **106**. The instrument **200**, much like a CNC mill, would then execute a semi-autonomous run by following a prescribed path calculated by the instrument controller **120** or the user (or a path generated on-the-fly). The instrument path's coverage would be limited by the available range of motion (and the user's ability to hold the instrument **200** still).

Another hybrid mode of operation involves dithering in which the cutting accessory **202** is moved in controlled pattern. This pattern may be one that results in the bur head shaping the bone **102** so as to result the finished surface having a specific degree of smoothness. In a dithering operation, the cutting accessory **202** may be moved from the home position so as to cause the bur head **204** to: move in an orbital pattern; move in a figure-eight pattern; and/or oscillate along a defined arc. This dithering is performed parallel to the surface of the local boundary.

VI. Applications

Referring to FIG. **65**, one possible application for the system is for bone sculpting as described above. In essence, the removed bone provides a "negative" cavity **1006** for an implant (e.g., knee implant). The instrument **200** could also cut complex 3-D shapes (i.e. mirror symmetric features). Likewise, the instrument **200** could be used to shave/smooth-out jagged bone and deformities.

Referring to FIG. **66**, the system **100** could be used for tunneling into bone, other tissue, or other materials. The instrument **200** can be configured to bore a straight hole **1008** that equals (or is slightly larger) than a diameter of the bur head **204**. As FIG. **66** shows inverted cone constraint geometry **1010** could be defined for accessing various parts of the body (e.g., spine).

Referring to FIG. **67**A-**67**C, use of the system **100** for targeting/alignment is shown. This allows a user (e.g., surgeon) to quickly locate a pre-planned or predefined location of a hole **1012** by "snapping" the tip of a drill bit **1014** to the hole's centerline (e.g., pre-drilling for pedicle screws). Once located, the display **1402**, could then be used to properly align the axis of the drill bit **1014** (or other cutting accessory) to the axis of the desired hole **1012**. With reference to screen shot of the display **1402** shown in FIG. **68**, the display shows dots **1016** that indicate the alignment is off-axis **1018** and needs to be moved. The instrument **200** corrects for deviations in alignment as drilling is underway by changing the pitch, yaw, or translation along the axis Z of the drill bit **1014**.

Referring to FIG. **69**, the instrument **200** may be used for cutting, ablating, or other surgical procedure near soft tissues and nerves **1020** with the ability to avoid these delicate areas. In this application, pre-op imaging and pre-planning to create constraint boundaries to avoid these sensitive areas. In some embodiments, the instrument **200** can be combined with a nerve monitor to prevent damaging nerves. This mapping can be performed during the procedure as the need arises.

Referring to FIG. **70**, the instrument **200** can be depth controlled. This allows the user to cut or drill to a specified depth (e.g., pedicle screws). The user, however, prevented from cutting too deeply or breaking thru other side of bone (e.g., bi-cortical screw). In this application, the work boundary is the depth surface of the bore.

Referring to FIG. **71**, the instrument **200** can also be used for custom implant shaping. In this application, a bur or other shaping tool can cut non-bone objects **1022** to a specified shape (e.g., plastic implants). The system could also be configured to modify objects to conform and match surfaces previously created while sculpting or manually cutting with the instrument **200**.

The system **100** and instrument **200** described herein are merely exemplary of the present invention. The invention could be utilized on several tissue types, including hard and soft tissues, for materials like plastic and metal, and for many different procedures, including, but not limited to cutting, ablating, drilling, general collision avoidance, and the like.

VII. Alternative Embodiments

The foregoing is directed to one specific version of system. Alternative versions of the system of this invention are possible. For example, instrument **200** can have a mechanism that vibrates (like an eccentric motor) while near a boundary, on boundary, or after exceeding a certain amount of deflection. This provides the user with further feedback that the distal end tip of the cutting accessory is approaching the boundary. Lights (e.g., LEDs) could be provided on the instrument **200**, such as the handle **502** to provide visual indication of the proximity of the cutting accessory to the working boundary. For instance, a green signal=good, yellow=on boundary, red=problem/stop.

Features may be provided on the instrument **200** to show the extent to which the bur head **204** is deflected from its home position. These features may be incorporated in the display **1402** on the instrument **200** (see FIG. **1** and FIG. **68**). The display **1402** is preferably mounted to the handle **502** to remain fixed relative to the handle **502** during use. In alternative embodiments, the display **1402** is attached to the upper assembly **300** to move with the upper assembly **300**. A driver (not shown) for the display **1402** is installed in the instrument controller **120**.

Surgical instrument **200** of this invention may be used with navigation systems other than the described system. For example, the instrument can be used with an image-less navigation system.

For bone sculpting applications, the display **1402** would give the status of the current amount of deflection of the cutting accessory **202**/bur head **204** or whether it is in the "Home" position. For Targeting/Alignment applications, the display **1402** would direct the user to align a cutting accessory's axis with a target axis. During the semi-autonomous cutting mode, the display **1402** could give visual instructions to inform the user where best to grossly position the bur head **204** or instrument **200**. In addition, the display **1402** could display navigation information (i.e. blocked LEDs for tracking purposes, percentage of cut completed, where additional material needs to be removed, etc.).

Data connection **1002** may be an IEEE 1394 interface, which is a serial bus interface standard for high-speed communications and isochronous real-time data transfer between the instrument controller **120** and the display **1402**. Data connection **1002** could use a company specific protocol.

Alternative assemblies may be provided for moving the cutting accessory to/from the home position. For example, mechanical assemblies that transfer power from the motors may include assemblies other than nuts disposed on lead screws. One such assembly could have a drive plate that is attached to the motor. The plate includes a pin that engages a link connected to the cutting accessory in order to displace the cutting accessory. Also, in some versions of the invention, belt drives may be employed to displace the cutting accessory. Still in another version of the invention the actuation of a motor may displace a rack. The rack is linked to the cutting accessory to displace the cutting accessory.

In another alternative version of the invention, the gimbal to which the cutting accessory is mounted is itself pivotally mounted to the body of the instrument. Thus the gimbal still provides the X- and Y-axes deflection of the cutting accessory. In these versions of the invention, the mechanism that holds the cutting accessory to the gimbal is moveably mounted to the gimbal. For example either the motor and coupling assembly or just the coupling assembly may be mounted to the gimbal so as to be able to move proximally or distally. In these versions of the invention, the motor that moves the cutting accessory distally and proximally may itself also be mounted to the gimbal to pivot with the gimbal. This displacement of the cutting accessory is, it should be appreciated, the displacement of the cutting accessory along axis Z.

Similarly, there is no requirement that, in all versions of the invention, mechanical energy be the source of power that positions the cutting accessory. For example the cutting accessory may be electromagnetically selectively displaced to/from the home position. In one version of this embodiment of the invention, instrument **200** may include solenoids. These solenoids are selectively actuated to retract/extend pins that are attached to the cutting accessory. The pins are selectively extended/retracted to cause the displacement of the cutting accessory to/from the home position. Alternatively, there may be other coils mounted internal to the instrument. These coils generate localized magnetic fields. The coils in each set of coils selectively attract or repel a set of magnets on the cutting accessory. The movement of the magnets results in the movement of the cutting accessory. In this version of the invention, the energization of a particular set of coils may selectively reply/attract a set of magnets that results in the simultaneous displacement of the cutting accessory on two or three axes.

Assemblies other than the fine pitched lead screws may function as the self locking feature of the instrument that blocks unintended back movement of the cutting accessory when the accessory is exposed to resistance. The exact structure of the self locking assembly is a function of the structure of the actuators that displace the cutting accessory. For example, if electromagnetic actuators are employed, the actuators serve as the self locking mechanism. Specifically, currents are applied to the coils to prevent resistive forces applied to the cutting accessory from preventing the unintended displacement of the cutting accessory. In some versions springs may also apply forces that inhibit the unintended movement of the cutting accessory. A cam assembly may also be used to lock the cutting accessory from unintended movement.

Instrument **200** may include components other than the described Hall-effect sensors internal to the motors to determine and control the position of the cutting accessory **202**. For example in some versions of the invention, absolute rotary position encoders or absolute angular position encoders may be used to monitor the rotational positions of the components that displace the cutting accessory. For monitoring some types of motion, for example, motion of the carriage along the axis Z, absolute linear position encoders may be incorporated into the instrument of this invention. In these versions of the invention, there may not be a need to provide supplemental position encoders to facilitate the zero state or home centering of the cutting accessory.

There is no requirement that in all versions of the invention the motor or other component that provides energy to the cutting accessory **202** be rigidly connected to the cutting accessory **202**. Thus in some versions of the invention, the energy output component may be flexibly linked to the cutting accessory **202**. If, for example, the cutting accessory **202** is a mechanically driven device, some type of drive cable or flexible joint may transfer the motive power to the cutting accessory **202**. For example the motor could be fixedly secured to the moveable carrier **305** while the cutting accessory **202** is pivotally connected to the carrier **305**. An advantage of this structure is that it reduces the mass of the component of the instrument **200** that needs to be moved towards/away from the home position.

In some versions of the invention, instrument **200** may be designed so that the extent to which the cutting accessory **202** may be displaced upon each of the X-, Y- and Z-axes is not equal to each other.

Also, there may be variations in the processes used to position the cutting accessory **202** in the home position. For example, typically, if the cutting accessory **202** is to be displaced along the axis Z, the accessory **202** is more often than not, moved rearward, proximally. Controller **120** therefore establishes a Z-axis home position for the carriage **302** that is typically forward of, distal to, the home position initially established during the homing process. This offsetting of the home position increases the extent to which, during the procedure, the cutting accessory **202** can be retracted proximally.

One means of so resetting the home position of the carrier **302** is to initially actuate the motor **224** so as to cause the carrier **302** to move to home position using the above-described homing process. Controller **120** then adds an offset count to the previously calculated target position count upon which the carrier **302** was moved to the displaced home position. This offset count is based on data previously stored in the controller **120**. This offset target position count is then forwarded to the motor controller **234**. Controller **234** actuates the motor **224** to cause the carrier **302** to move distally. The carrier **302** is moved until the cumulative count from the motor equals the offset target position count. Once the carrier **302** is so repositioned in the offset home position, the controller **120** zeros out the cumulative count.

When the Z-axis home position of the cutting accessory **202** is so offset, the range of motion of the accessory tip or bur head **204** along the axis Z does not equal the range of motion of the tip or bur head **204** along the X- and Y-axes. Thus, in these implementations of the invention, the boundary of the spaced volume through which the accessory tip or bur head **204** moves when displaced to its maximum deflected positions is not spherical.

Likewise, it should be understood that in other versions of the invention, the full range of deflection of the cutting accessory tip or bur head **204** in the X- and Y-axes may not be equal.

The extent to which the speed of the instrument motor **206** is attenuated may also vary from what was described with respect to FIG. **64**. For example, in some versions of the invention as soon as there is any deflection of the cutting accessory **202** from the home position, the controller **120** causes some attenuation of the motor speed. This provides the practitioner some immediate aural and tactile feedback that the bur head **204** is at the working boundary **106**. The level of this speed attenuation remains constant as long as the deflection is within a set percentage of the maximum cumulative deflection. Once the deflection exceeds this threshold percentage, the controller **120** asserts instruction packets to the console **130** that serve to increase the extent to which the motor speed is attenuated. This provides a second set of aural and tactile feedback signals to the practitioner that it may be appropriate to further adjust the position of and force applied to the cutting accessory **202**.

Further in some versions of the invention, the controller **120** may cause the speed of the instrument motor **206** to be attenuated as a function of the proximity of the accessory tip or bur head **204** to the working boundary **106**. Specifically, there may be instrument packets sent to the console **130** that result in a first level of speed attenuation when it is determined that the accessory tip or bur head **204** is a first distance from the working boundary **106**. Once the accessory tip or bur head **204** intersects or crosses the working boundary **106**, the controller **120** causes the motor speed to be attenuated to a second level. Then, as the extent to which the bur head **204** is diverted from the home position increases beyond a threshold level, the controller **120** increases the attenuation of the motor speed. This stepped attenuation of motor speed provides the practitioner with a stepped indication of the proximity of the accessory tip or bur head **204** to the working boundary **106**.

Also, the processes by which the controller **120** determines the relative position of the distal end tip of the cutting accessory **202** relative to the working boundary **106** may differ from what has been described. Ideally, the navigation unit **108** should be able to provide data from which this position can be determined at a frequency equal to the frequency with which the computer recalculates the extent to which the cutting accessory **202** is to be moved from the home position. In actuality, navigation systems are typically not able to perform measurements at these frequencies. One potential solution is to have the controller **120** use the last few frames of data from the navigation unit **108** to determine the velocity of the direction of the instrument **200** towards/away from the bone. Based on this determination, the controller **120** generates extrapolated estimations of the relative location of the instrument **200** to the bone after the last true position information received from the navigation unit **108**. Based on these predictions of instrument position, the controller **120** determines whether or not and the extent to which cutting accessory **202** should be diverted from the home position.

Still other means of providing measured or arcuate estimates of the relative position and orientation of the distal end of the cutting accessory **202** relative to the working boundary **106** are associated with features of the navigation unit **108** that are not within the scope of the current invention.

Likewise, depending on the processing speed and/or the ability to transmit data to/from the controller **120**, it may not always be necessary to determine the relative position of the cutting accessory **202** based on the assumption that the accessory **202** is in the home position. It is within the scope of this invention that this determination be made based not only on the relative position of the trackers **114**, **116**. This additional data includes data defining the extent to which the distal end of the cutting accessory **202** is diverted from the home position.

Likewise there is no requirement that all components be in all versions of the invention. For example, it may be that in some versions of the system **100** that a single set of sensors provide the signals used to both initially center or home the cutting accessory **202** and then to monitor the extent to which the cutting accessory **202** is displaced from the home position.

Also, the degree of required alignment should be understood to be a function of the type of cutting accessory **202** fitted to the instrument **200**. For example, when forming a bore hole in the active mode, it is often necessary to more precisely position the cutting accessory **202** when the accessory **202** is a drill bit as opposed to a bur head **204**.

In alternative embodiments, the controllers **230**, **232** and **234** that regulate the actuators that set the position of the cutting accessory **202** are mounted in the control unit **120**. This eliminates the need to provide the instrument **200** with a structure like shell **670**.

It should likewise be appreciated that precision of the operation of instrument **200** can be enhanced by increasing the frequency with which the accessory to boundary determination and subsequent instrument control cycles are preformed. For example, it may be desirable to provide the instrument controller **120** with hardware and software capable of executing these cycles at a frequencies of 2 kHz and higher, 4 kHz and higher and 8 kHz and higher.

In some embodiments the tracking devices **114**, **116** attached to the instrument **200** and the anatomy may be non-optically based trackers such as tracking devices that transmit or receive electromagnetic waves, ultrasonic waves, RF signals, or other tracking devices known to those having ordinary skill in the art.

VIII. Pencil Grip Embodiment

In addition to the alternative embodiments described in the section above, FIGS. **72-111** show another embodiment of the surgical instrument, hereinafter numbered **1200**, that has a pencil grip configuration. Surgical instrument **1200** can be used in the tracking and control system **100** shown in FIG. **1** and described above. As set forth above, the tracking and control system **100** tracks the positions and orientations of the target volume **104** and the surgical instrument **1200** to keep the tip or bur head **204** of the cutting accessory **202** at the target volume **104**. Surgical instrument **1200** can be used in the same applications as surgical instrument **200** discussed above. Surgical instrument **1200** typically includes a cord **1203** for connection to the tracking and control system **100**, and specifically to the instrument controller **120**.

With reference to FIGS. **72-74**, the surgical instrument **1200** includes a distal assembly **1202**, also referred to as a drive assembly **1202**, and a proximal assembly **1204**, also referred to as the hand-held portion **1204**. The hand-held portion **1204** is manually supported and moved by a user. The user operates the instrument **1200** by grasping and supporting hand-held portion **1204** and the instrument **1200** is unsupported by other mechanical arms, frames, etc. As set forth with the embodiments described above, the tracking device **114** is attached to the hand-held portion **1204** for tracking the instrument **1200**.

The working portion, e.g., the cutting accessory **202**, is movably coupled to the hand-held portion **1204**. As set forth in greater detail below, the distal assembly **1202** releasably holds the working portion, e.g., the cutting accessory **202**, drives the working portion to perform the medical/surgical task on the tissue of the patient, and moves the working portion in the axis Z, as identified in FIGS. **72** and **73**, to prevent the distal tip or bur head **204** of the accessory **202** from colliding with or breaching the work boundary **106** of the target volume **104** to which the cutting accessory **202** is being applied.

The proximal assembly **1204** engages the distal assembly **1202** and moves the distal assembly **1202** to adjust the pitch and yaw of the cutting accessory **202** to prevent the distal tip or bur head **204** of the accessory **202** from colliding with or breaching the work boundary **106** of the target volume **104**. As set forth above, "pitch" is the up-down angular orientation (i.e., the X-axis shown in the Figures) of the longitudinal axis A of the distal assembly **1202** and the cutting accessory **202** relative to a horizontal plane through the center of a gimbal bushing **1256** and "yaw" is the right-left angular orientation (i.e., the Y-axis shown in the Figures) of the longitudinal axis A of the distal assembly **1202** and the cutting accessory **202** relative to a vertical plane through the center of the gimbal bushing **1256**. FIGS. **75**A-C, for example, show three different positions of adjustment in the pitch of the distal assembly **1202** relative to the proximal assembly **1204**. The range of motion of the tip **204** of the cutting accessory **202** relative to the distal assembly **1202** as defined by the control system **100** is shown as a circle C in FIGS. **75**A-C and **85-87**. Various views of the distal assembly **1202**, or portions thereof, are shown in FIGS. **74-106**. With reference to FIGS. **75**A-C, the proximal assembly **1204** includes an outer casing **1206** and the distal assembly **1202** includes a casing **1208** that remains rotationally fixed about the longitudinal axis A relative to the outer casing **1206** of the proximal assembly **1204**. Proximal assembly **1204** engages the distal assembly **1202** and adjusts the pitch and yaw of the distal assembly **1202** relative to the proximal assembly **1204**, as set forth further below.

With reference to FIGS. **75**A-C, a nose tube **1218** extends from the casing **1208** and supports the cutting accessory **202**. The nose tube **1218** defines a nose tube bore **1220** (as best shown in FIGS. **76** and **80**). A collet assembly **1211** (shown in isolation in FIGS. **81-84**) is rotatably disposed in the nose tube bore **1220** for releasably engaging the cutting accessory **202** in the nose tube bore **1220**, as set forth further below.

A drive mechanism **1201** is coupled to the working portion for rotating the working portion about the longitudinal axis A as indicated by arc R. The drive mechanism **1201** includes a drive motor **1212**, also referred to as an accessory motor **1212**, disposed in the casing **1208** for driving the collet assembly **1211** and the cutting accessory **202**, e.g., for rotating the cutting accessory **202**.

As set forth further below, the drive assembly **1202** and the cutting accessory **202** move relative to the hand-held portion **1204** in a plurality of degrees of freedom. A plurality of actuators, e.g., lead screw motor **1240**, yaw motor **1302**, and pitch motor **1304**, are operatively coupled to the working portion for moving the working portion in a plurality of degrees of freedom relative to the hand-held portion **1204**.

The drive mechanism **1201** moves in at least one degree of freedom relative to the hand-held portion **1204** and, more specifically, the drive motor **1212** moves in at least two degrees of freedom relative to the hand-held portion **1204** relative to the hand-held portion **1204**. At least one of the actuators, and more specifically, the yaw motor **1302** and the pitch motor **1304**, move the drive mechanism **1201** and the drive motor **1212** in pitch and yaw relative to the hand-held portion **1204**. Specifically, the casing **1208** is movable by at least one of the actuators, e.g., the yaw motor **1302** and the pitch motor **1304** in pitch and yaw relative to the hand-held portion **1204**. The drive mechanism **1201** and the drive motor **1212** are fixed along the longitudinal axis A relative to the hand-held portion **1204**. In this embodiment, the longitudinal axis A moves in pitch and yaw relative to the hand-held portion **1204**.

As best shown in FIGS. **75**A-C and **85-87**, the plurality of actuators, e.g., lead screw motor **1240**, yaw motor **1302**, and pitch motor **1304**, are capable of moving the working portion relative to the hand-held portion **1204** in at least three degrees of freedom including pitch, yaw, and translation along the longitudinal axis A. In an embodiment where the working portion, i.e., the cutting accessory **202**, comprises a bur head **204**, the drive motor **1212** moves in four degrees of freedom relative to the hand-held portion **1204**, i.e., the drive motor **1212** rotates the bur head **204**.

The drive assembly **1202** supports the working portion and one of the actuators and is movable by at least another of the actuators. Specifically the drive assembly **1202**, and more specifically, the casing **1208**, supports the lead screw motor **1240**, also referred to as axial motor **1240**, and the drive motor **1212**. The lead screw motor **1240** translates the working portion along the longitudinal axis A. The drive assembly **1202** is movable by the yaw motor **1302** and the pitch motor **1304**. The yaw motor **1302** and pitch motor **1304** move the drive motor **1212**, the working portion, and the lead screw motor **1240** in pitch and yaw relative to the hand-held portion **1204**.

The drive motor **1212** can be controlled by instrument driver **130** in the same manner as motor **206** is controlled in the prior described embodiments. A shaft **1210**, as discussed further below, is disposed in the casing **1208** and extends from the drive motor **1212** to the collet assembly **1211** for transmitting rotation from the drive motor **1212** to the collet assembly **1211** for driving the cutting accessory **202**.

The drive motor **1212** includes a rotor **1214**, as shown for example in FIG. **84**, that is rotatably coupled to the casing **1208** to drive the cutting accessory **202**. The rotor **1214** can include at least one bearing **1213** engaging the casing **1208** to rotatably couple the rotor **1214** to the casing **1208** and allow rotation of the rotor **1214** relative to the casing **1208**.

The rotor **1214** includes a keyed bore **1215**. The shaft **1210**, which is shown for example in FIG. **84**, includes a first end **1217** configured to engage the keyed bore **1215** of the rotor **1214** such that rotation of the rotor **1214** is transmitted to the shaft **1210**. The cross-sectional shape of the keyed bore **1215** and the first end **1217** are double-D shaped as shown in FIG. **84** but, alternatively, can be any suitable shape without departing from the nature of the present invention.

The collet assembly **1211** rotatably couples the drive shaft **1210** to the cutting accessory **202** so that the cutting accessory **202** rotates in direction R about the longitudinal axis A upon rotation of the drive shaft **1210**. The collet assembly **1211**, which is shown in isolation in FIGS. **81-84**, is rotatably coupled to the nose tube **1218** in the nose tube bore **1220**. With reference to FIG. **76**, a stack-up **1285** of various components is disposed in the nose tube bore **1220** between the collet assembly **1211** and a lip **1281**. A ring **1283**, as best shown in FIG. **76**, is fixed in the nose tube bore **1220**, typically by press fit, adjacent the collet assembly **1211** to retain the collet assembly **1211** and the stack-up **1285** in the nose tube bore **1220**.

The collet assembly **1211** can include at least one bearing **1219** (e.g., shown in FIG. **76**) engaging the nose tube **1218** to rotatably couple the collet assembly **1211** to the nose tube **1218** and allow rotation of the collet assembly **1211** relative to the nose tube **1208**.

The collet assembly **1211** includes a keyed end **1221** and the shaft **1210** includes a second end **1223** configured to engage the keyed end **1221** such that rotation of the shaft **1210** is transmitted to the collet assembly **1211**. The second end **1223** and the keyed end **1221** are moveable relative to each other. Under normal operating conditions, the collet assembly **1211** and the shaft **1210** move together as a unit and, when the collet assembly **1211** is moved to lock and unlock the cutting accessory **202**, as set forth further below, the keyed end **1221** and the second end **1223** of the shaft **1210** slide relative to each other. The cross-sectional shape of the keyed end **1221** and the second end **1223** of the shaft **1210** are double-D shaped as shown in FIG. **84** but, alternatively can be any suitable shape without departing from the nature of the present invention.

With reference to FIG. **76**, the nose tube **1218** supports the working portion, e.g., cutting accessory **202**, and is movable relative to the casing **1208** in translation in the Z direction along the longitudinal axis A, i.e., the nose tube **1218**, which is typically cylindrical, adjusts the position of the cutting accessory **202** along the longitudinal axis A.

With reference to FIG. **85-89**, during normal operation, the nose tube **1218** is axially fixed relative to the shaft **1210** along the longitudinal axis A. As such, as the nose tube **1218** moves axially along the longitudinal axis A, the nose tube **1218** moves the shaft **1210** along the longitudinal axis A, as shown in FIGS. **85-87**. When the collet assembly **1221** is moved to lock and unlock the cutting accessory **202**, the nose tube **1218** and the shaft **1210** move relative to each other, as shown in FIGS. **88** and **89** and as set forth further below.

With reference to FIGS. **78** and **79**, nose tube bore **1220** rotatably receives the shaft **1210** and the cutting accessory **202**. As best shown in FIG. **76**, bearings **1222** are disposed in the nose tube bore **1220** for rotatably supporting the cutting accessory **202** in the nose tube bore **1220**.

With reference to FIGS. **85-87**, the casing **1208** telescopically receives the nose tube **1218**. As best shown in FIG. **90**, the casing **1208** defines channels **1224**. As best shown in FIGS. **79** and **80**, the nose tube **1218** includes a flange **1226** including protrusions **1228** engaging the channels **1224**. Channels **1224** are circumferentially spaced from one another about the casing **1208**. The protrusions **1228** are circumferentially spaced from one another about the nose tube **1218** to mate with the channels **1224**. Channels **1224** extend parallel to the longitudinal axis A and are sized and shaped to restrain the protrusions **1228** to movement along the longitudinal axis A. It is appreciated that the protrusions **1228** and channels **1224** can be defined on either of the casing **1208** and the nose tube **1218**, and the casing **1208** and the nose tube **1218** can include any number of corresponding protrusions **1228** and channels **1224** without departing from the nature of the present invention. The casing **1208** can, for example, include a bushing **1265** that is fixed to the rest of the casing **1208** and defines the channels **1224**. The bushing **1265** is typically formed from a different type of material than the casing **1208**. The bushing **1265** is typically formed of a material that provides a low-friction interface with the nose tube **1218** and is typically formed of a non-magnetic material to allow for position sensing.

As best shown in FIGS. **85-89** and **91-92**, distal assembly **1202** includes a lead screw **1230** rotatably mounted in the casing **1208**. The lead screw **1230** is typically cylindrical. Bearings **1232** are disposed in the casing **1208** between the casing **1208** and the lead screw **1230**.

With reference to FIGS. **85-89**, the lead screw **1230** threadably engages the nose tube **1218**. The nose tube **1218** telescopically extends from the lead screw **1230** along the longitudinal axis A and is telescopically adjustable along the longitudinal axis A relative to the lead screw **1230**. Specifically, lead screw **1230** defines a lead screw bore **1234** and interior threads **1236** in the lead screw bore **1234**. Nose tube **1218** defines exterior threads **1238**. Lead screw **1230** telescopically receives the nose tube **1218** in the lead screw bore **1234**. The exterior threads **1238** of the nose tube **1218** threadedly engage the interior threads **1236** in the lead screw bore **1234**. The interior threads **1236** and the exterior threads **1238** have a fine pitch and lead angle to prevent back driving, i.e., to encourage self-locking.

As set forth above, the actuators include the lead screw motor **1240**. The lead screw motor **1240** includes a hollow rotor **1287**, as identified in FIGS. **75**A-C and **77**, that rotatably receives the drive shaft **1210** therein such that the drive shaft **1210** rotates within the hollow rotor **1287** and relative to the hollow rotor **1287** so as to rotatably drive the working portion.

The nose tube **1218** is threadedly coupled to the hollow rotor **1287**. Specifically, lead screw motor **1240**, as best shown in FIGS. **85-87**, is engaged with the lead screw **1230** to rotate the lead screw **1230** and the nose tube **1218** is threadedly engaged with the lead screw **1230**.

The nose tube **1218** is rotationally constrained in the casing **1208** such that the rotation of the hollow rotor **1287** telescopes the nose tube **1218** relative to the casing **1208**. In other words, since the engagement of the corresponding protrusions **1228** and channels **1224** prevents rotation of the nose tube **1218** relative to the casing **1208** and allows translation of the nose tube **1218** relative to the casing **1208** along the longitudinal axis A, the nose tube **1218** remains rotationally fixed relative to the casing **1208** as the lead screw motor **1240** rotates the interior threads **1236** of the lead screw **1230** relative to the exterior threads **1238** of the nose tube **1218**. This relative rotation of the interior threads **1236** and the exterior threads **1238** moves the nose tube **1218** along the longitudinal axis A relative to the casing

1208. The protrusions 1228 slide in the channels 1224, respectively, as the nose tube 1218 moves along the longitudinal axis A. As a result, the cutting accessory 202, which is carried by the nose tube 1218 during operation, is translated along the longitudinal axis A in response to rotation of the lead screw 1230.

FIGS. 85-87, for example, show the nose tube 1218 moved to different locations relative to the casing 1208 along the longitudinal axis A. Specifically, in FIG. 85 the nose tube 1218 is nearly fully extended and in FIG. 87 the nose tube 1218 is nearly fully retracted. FIG. 86 shows a position between those shown in FIGS. 85 and 87. Specifically, FIG. 86 shows the nose tube 1218 in a "home" position. When the nose tube 1218 moves relative to the casing 1208, the collet assembly 1211, the cutting accessory 202, and all other components housed in the nose tube 1218 move with the nose tube 1218.

As shown in FIGS. 85-87, the keyed bore 1215 telescopically receives the shaft 1210. The shaft 1210 slides along the keyed bore 1215 as the shaft 1210 is moved into and out of the keyed bore 1215 as the nose tube 1218 is extended and retracted along the longitudinal axis A. As set forth above, the first end 1217 of the shaft 1210 is configured to engage the keyed bore 1215 such that rotation is transmitted from the rotor 1214 to the shaft 1210. As also set forth above, the second end 1223 is rotationally locked to the keyed end 1221 of the collet assembly 1211. As such, when the nose tube 1218 is retracted or extended, the shaft 1210 slides in the keyed bore 1215 and transmits rotation to the collet assembly 1211 regardless of the position of the shaft 1210 in the keyed bore 1215.

With continued reference to FIGS. 85-87, bearing 1243 rotatably supports the shaft 1210 in the keyed bore 1215. Bearing 1243 is disposed between a rotor of lead screw motor 1240 and shaft 1210. Rotor of drive motor 1212 rotates concentrically within lead screw motor 1240, while rotor of lead screw motor 1240 rotates about rotor of drive motor 1212. Shaft 1210 is longitudinally slideable relative to bearing 1243 during retraction and extension of the nose tube 1218.

Bearing 1245 rotatably supports the shaft 1210 in the nose tube 1218. Shaft 1210 is longitudinally slideable relative to bearing 1245 when the collet assembly 1221 is moved to lock and unlock the cutting accessory 202.

With reference to FIGS. 76 and 90, the flange 1226 can define a cavity 1242 for receiving a position identifier such as magnet 1255. In such an embodiment, the casing 1208 or the bushing 1265 supports one or more position sensors, e.g., magnetic sensors (not shown), such as a Hall-effect sensor, that measures the proximity of the magnet 1255 to track the location of the nose tube 1218 along the longitudinal axis A. The position sensor communicates with the control system 100.

As set forth above, the collet assembly 1211 releasably engages the cutting accessory 202. The collet assembly 1211 is configured to release the cutting accessory 202 in response to actuation of the lead screw motor 1240 beyond a predefined limit of actuation. The collet assembly 1211 engages the cutting accessory 202 to transmit movement, e.g., torque, from the shaft 1210 to the cutting accessory 202. Specifically, the collet assembly 1211 rotationally fixes the cutting accessory 202 to the shaft 1210. The collet assembly 1211, for example, could be of the type shown in U.S. Pat. No. 5,888,200 to Walen, which is hereby incorporated by reference, or the type shown in U.S. Pat. No. 6,562,055 to Walen, which is hereby incorporated by reference.

With reference to FIGS. 81-84, the collet assembly 1211 includes an outer sleeve 1225 and an inner member 1227 telescopically received in the outer sleeve 1225. A clamping member 1267, i.e., a collet, as shown in FIG. 83, is sandwiched between the inner member 1227 and the outer sleeve 1225. As set forth further below, the inner member 1227 selectively biases the clamping member 1267 into engagement with the cutting accessory 202.

The clamping member 1267 includes a ring 1269 and at least one arm 1229 extending from the ring 1269. FIG. 85 shows two arms 1229. It should be appreciated that the clamping member 1267 can include any number of arms 1229 without departing from the nature of the present invention.

With reference to FIGS. 81 and 82, the inner member 1227 defines a bore 1231 for receiving the cutting accessory 202. The inner member 1227 defines at least one opening 1233, also shown in FIG. 84, in communication with the bore 1231. Each arm 1229 includes a foot 1235 that can extend through the opening 1233 and into the bore 1231 to engage the cutting accessory 202, as set forth further below.

The inner member 1227 is slideable longitudinally relative to the outer sleeve 1225 and the arms 1229 between a locked position (shown in FIG. 88) and an unlocked position (shown in FIG. 89). Specifically, in the locked position, the outer sleeve 1225 provides a retention force on the arms 1229 to retain the feet 1235 in the opening 1233. In the unlocked position, the outer sleeve 1225 is moved relative to the arms 1229 to eliminate the retention force and the feet 1235 are free to move out of the opening 1233. Specifically, when the outer sleeve 1225 is in the unlocked position, the feet 1235 naturally remain in the opening 1233, however, the arms 1229 are free to bend allowing the feet 1235 to move out of the opening 1233. As such, when the cutting accessory 202 is inserted into the bore 1231, the cutting accessory 202 moves the feet 1235 outwardly.

The collet assembly 1211 includes a pin 1251 that abuts the shaft 1210, as best shown in FIG. 88. A spring 1279 pre-loads the shaft 1210 into engagement with the pin 1251. In particular, a collar 1299 is fixed to shaft 1210 and spring 1279 acts against bearing 1245, which is axially fixed to nose tube 1218, to urge collar 1299 distally. As set forth above, the shaft 1210 is longitudinally slideable relative to the bearing 1245 when the collet assembly 1211 is moved to lock and unlock the cutting accessory 202, and the spring 1279 urges the shaft 1210 to move distally with the nose tube 1218 during normal operation of the nose tube 1218.

The outer sleeve 1225 defines a hole 1275, shown in FIGS. 83 and 84, that receives the pin 1251 such that the outer sleeve 1225 and the pin 1251 move together as a unit relative to the inner member 1227. The inner member 1227 defines a slot 1277 that receives the pin 1251.

When the outer sleeve 1225 and the inner member 1227 move relative to each other, the shaft 1210 slides longitudinally in the keyed end 1221 of the inner member 1227 and the pin 1251 slides along the slot 1277. In other words, the inner member 1227 moves relative to the outer sleeve 1225, the pin 1251, and the shaft 1210. As set forth further below, to move to the unlocked position, the shaft 1210 exerts force on the pin 1251 to hold the outer sleeve 1225 in place relative to the casing 1208 and the nose tube 1218 exerts force on the inner member 1227 to move the inner member 1227 relative to the outer sleeve 1225.

The outer sleeve 1225 includes a boss 1239 that rides along the arms 1229. In the locked position, the boss 1239 of the outer sleeve 1225 retains the feet 1235 in the slots 1233 and in the bore 1231 as shown in FIG. 88. The outer sleeve **1225** defines holes **1249** through which the arms **1229**/feet **1235** can extend in the unlocked position.

A spring **1247** is disposed between the outer sleeve **1225** and the inner member **1227**. The spring **1247** biases the outer sleeve **1225** and the inner member **1227** toward the locked position. The spring **1247** abuts the ring **1269** of the clamping member **1267** and abuts a washer **1273**. The spring **1247** biases the ring **1269** against a flange **1271** of the inner member **1227** and biases the washer **1273** against the pin **1251**, which is fixed relative to the outer sleeve **1225**.

As best shown in FIGS. **88** and **89**, the cutting accessory **202** defines flats **203**. To engage the cutting accessory **202** with the collet assembly **1211**, the outer sleeve **1225** and inner member **1227** are moved to the unlocked position such that the boss **1239** moves along the arms **1229** away from the feet **1235**. The cutting accessory **202** is then inserted into the bore **1231** and bias the feet **1235** out of the bore **1231** until the flats **203** are aligned with the feet **1235**. Feet **1235** spring back into the bore **1231** when the flats **203** are aligned with the feet **1235** such that the feet **1235** engage one of the flats **203**. The inner member **1227** is then moved relative to the outer sleeve **1225** to the locked position to lock the feet **1235** in engagement with the flat **203** to rotationally and translationally lock the cutting accessory **202** to the collet assembly **1211**.

The outer sleeve **1225** and inner member **1227** can be moved between the locked position and the unlocked position by selective movement of the lead screw **1230**. As set forth above, various positions within the normal operating range of the nose tube **1218** are generally shown in FIGS. **85-87**. The shaft **1210** includes a flange **1241**. As the nose tube **1218** is extended and retracted, the flange **1241** moves relative to the bearing **1243**. As shown in FIG. **87**, the flange **1241** is near the bearing **1243** when the nose tube **1218** is nearly fully retracted. When the nose tube **1218** is fully retracted, the flange **1241** is slightly spaced from, or alternatively, in contact with, the bearing **1243**.

The outer sleeve **1225** and inner member **1227** can be moved to the unlocked position by retracting the nose tube **1218** beyond the near retracted position of FIG. **88**, i.e., beyond the predefined limit of actuation for normal operation. When the nose tube **1218** is retracted beyond the retracted position, the flange **1241** of the shaft **1210** abuts the bearing **1243** and prevents further movement of the shaft **1210** into the keyed bore **1215**, as shown in FIGS. **88** and **89**.

As set forth above, the inner member **1227** and the nose tube **1218** are translationally fixed to each other and the inner member **1227** is telescopically received in the outer sleeve **1225**. Spring **1247** urges the outer sleeve **1225** and the inner member **1227** such that the arms **1229** are in the locked position. When the flange **1241** abuts the bearing **1243** and the nose tube **1218** is further retracted, the shaft **1210** prevents further movement of the pin **1251** and thus the outer sleeve **1225** and, as such, further retraction of the nose tube **1218** moves the inner member **1227** relative to the outer sleeve **1225** thereby compressing the spring **1247**, as shown in FIG. **89**. In other words, the shaft **1210** abuts the pin **1251**, which is fixed to the outer sleeve **1225**, to prevent further movement of the outer sleeve **1225** while the inner member **1227** continues to move and compress the spring **1247**. As such, the inner member **1227** is moved relative to the outer sleeve **1225** to move the arms **1229** to the unlocked position, as set forth above, in response to actuation of the lead screw motor **1240** beyond the predefined limit of actuation.

During normal operation, e.g., during use for a navigated surgical procedure, the nose tube **1218** can travel between the extended and retracted positions and does not retract beyond the retracted position. An additional step outside of the normal operation is required to engage the cutting accessory **202** with the nose tube **1218** or disengage the cutting accessory **202** from the nose tube **1218**. For example, an input device (not shown) such as a button, switch, etc., can be mounted to the outer casing **1206** to provide input that allows for the nose tube **1218** to be retracted beyond the retracted position, as set forth above, to move the arms **1229** to the unlocked position. Alternatively, movement of the nose tube **1218** beyond the retracted position can be controlled with software.

It should be appreciated that the collet assembly **1211** shown in FIGS. **81-84** is shown merely for exemplary purposes and the shaft **1210** can engage the cutting accessory **202** in any suitable manner without departing from the nature of the present invention.

In another embodiment shown in FIGS. **93** and **94**, the nose tube **1218** can include an anti-backlash device **1224** that engages the lead screw **1230** and the nose tube **1218**. The anti-backlash device **1224** includes an insert **1246** with a threaded shoulder **1248** that threadedly engages the interior threads **1236** of the lead screw **1230**. A coupling **1250** is fixed to the nose tube **1218** in the nose tube bore **1220**. The coupling **1250** is typically fixed in the nose tube bore **1220** by press fit engagement, however, the coupling **1250** can be fixed in the nose tube bore **1220** in any suitable fashion without departing from the nature of the present invention. The insert **1246** and the coupling **1250** define a bore **1247** that rotatably receives the shaft **1210**. A bearing **1249** can be disposed between the insert **1246** and the shaft **1210**.

Insert **1246** includes circumferentially spaced fingers **1252** and the coupling **1250** includes slots **1253**. The fingers **1252** and the slots **1253** are engaged in alternating arrangement circumferentially about the longitudinal axis A. The fingers **1252** of the insert **1246** and the slots **1253** of the coupling **1250** interlock with each other circumferentially about the longitudinal axis A to prevent relative rotation and slidingly engage each other along the longitudinal axis A to allow for relative translation along the longitudinal axis A during assembly of the anti-backlash device **1224**. As such, the insert **1246** can slide along the longitudinal axis A relative to the nose tube **1218**.

A spring element **1254** is disposed between the insert **1246** and the nose tube **1218** and extends along the longitudinal axis A between the insert **1246** and the nose tube **1218**. The spring element **1254** can be an O-ring of elastomeric material, but alternatively can be any type of suitable spring element without departing from the nature of the present invention. The spring element **1254** exerts axial pressure on the nose tube **1218** along the longitudinal axis A to bias the exterior threads **1238** of the nose tube **1218** against the interior threads **1236** of the lead screw **1230**, which eliminates play between the exterior threads **1238** and interior threads **1236** to eliminates backlash during changes in rotational direction of the lead screw **1230** relative to the nose tube **1218**.

As best shown in FIG. **78**, the casing **1208** supports and at least partially encloses the rest of the distal assembly **1202** such as the nose tube **1218**, lead screw **1230**, lead screw motor **1240**, etc. As such, adjustment of the yaw and pitch of the casing **1208**, as set forth further below, also adjusts pitch and yaw of the rest of the distal assembly **1202** and the cutting accessory **202** held by the distal assembly **1202**.

With reference to FIG. **95**, the working portion, e.g., cutting accessory **202**, moves about the gimbal **1258** in at least two degrees of freedom relative to the hand-held portion **1204**. Specifically, the working portion is adjustable in pitch and yaw about the gimbal **1258**. The gimbal **1258** is fixed along the longitudinal axis A relative to the hand-held portion **1204**. The nose tube **1218** translates relative to the gimbal **1258** along longitudinal axis A.

The gimbal bushing **1256** is connected to the outer casing **1206**. The gimbal **1258** is attached to the casing **1208** of the distal assembly **1202** and the gimbal bushing **1256** holds the gimbal **1258** to pivotally secure the casing **1208** of the distal assembly **1202** to the outer casing **1206** of the proximal assembly **1204**. The gimbal bushing **1256** and the gimbal **1258** typically have matching inner and outer surfaces so that gimbal **1258** can pivot relative to gimbal bushing **1256**. The gimbal bushing **1256** shown for example in the Figures is split, i.e., includes two portions. The gimbal bushing **1256** is formed of a low friction material such as, for example, brass or bronze.

Gimbal **1258** is a ring shaped structure that has a frusto-spherical shape, i.e., an outer shape of a sphere the opposed ends of which have been removed. The gimbal **1258** is attached to the casing **1208** of the distal assembly **1202** so the distal assembly **1202** and the cutting accessory **202** are able to pivot relative to the proximal assembly **1204**. The gimbal **1258** is located around the center of gravity G of distal assembly **1202** to minimize the mass moment of inertia of the distal assembly **1202** as the distal assembly **1202** is pivoted to maximize the angular acceleration for a given supplied torque.

With continued reference to FIG. **95**, the gimbal **1258** defines a slot **1260** and the proximal assembly **1204** includes a peg **1262** fixed to and extending from the gimbal bushing **1256** into the slot **1260**. The slot **1260** extends longitudinally along the gimbal **1258**. The peg **1262** and the slot **1260** are sized and shaped to prevent rotation of the distal assembly **1202** about the longitudinal axis A relative to the proximal assembly **1204** while allowing pitch and yaw adjustment of the distal assembly **1202** relative to the proximal assembly **1204**.

The proximal assembly **1204** includes an adjustment assembly **1264** for adjusting the pitch and yaw of the distal assembly **1202** relative to the proximal assembly **1204**. The proximal assembly, e.g., outer casing **1206**, is held and gripped by the user. As shown in FIGS. **74-75**C, the outer casing **1206** of the proximal assembly **1204** houses the adjustment assembly **1264**. Various views of the adjustment assembly **1264**, or portions thereof, are shown in FIGS. **97-106**.

With reference to FIG. **101**, adjustment assembly **1264** includes a frame **1266** that houses a yaw adjustment device **1268**, i.e., a yaw adjustment mechanism **1268**, and a pitch adjustment device **1270**, i.e., a pitch adjustment mechanism **1270**. The frame **1266** is fixed within the outer casing **1206** of the proximal assembly **1204**. The yaw adjustment device **1268** and the pitch adjustment device **1270** move relative to the frame **1266** and engage the distal assembly **1202** to move the distal assembly **1202** relative to the frame **1266** and the outer casing **1206** to adjust the yaw and pitch, respectively, of the distal assembly **1202** relative to the proximal assembly **1204**.

With continued reference to FIG. **101**, yaw adjustment device **1268** and the pitch adjustment device **1270** each include a pair of lead screws **1272**, which are threaded, and a carriage **1274** that threadedly engages the lead screws **1272**. The lead screws **1272** typically include a fine pitched thread to prevent backdrive (see above). The components of the yaw adjustment device **1268** and the pitch adjustment device **1270**, e.g., the pair of lead screws **1272** and the carriage **1274**, are identical to each other and are arranged in the frame **1266**. Specifically, the frame **1266** extends about an axis, and the yaw adjustment device **1268** and the pitch adjustment device **1270** are spaced from each other along the axis and are rotated 90° relative to each other about the axis.

With reference to FIG. **101**, lead screws **1272** of the yaw adjustment device **1268** and the pitch adjustment device **1270** are rotatably engaged with the frame **1266**. Bearings **1276** are disposed between the lead screws **1272** and the frame **1266** to rotatably retain the lead screws **1272** in the frame **1266**. With reference to FIG. **101**, lead screws **1272** each define a threaded surface **1278** and the carriage **1274** defines a pair of threaded bores **1280** for threadedly receiving the lead screws **1272**. As set forth further below, simultaneous rotation of the pair of lead screws **1272** moves the carriage **1274** along the lead screws **1272**. The carriage **1272** includes pockets (not numbered) for receipt of position identifiers, e.g., magnets, that communicate with position sensors, e.g., Hall-effect sensors. Such position sensors can be fixed, for example, to the frame **1266**. The position sensors communicate with the control system **100**.

In another embodiment shown in FIGS. **105** and **106**, the carriages **1274** can each include an anti-backlash device **1282** disposed on each of the lead screws **1272**. Each anti-backlash device **1282** includes a cap **1284** that defines a threaded bore **1286** that threadedly engages the lead screw **1272**.

Cap **1284** is coupled to the lead screw **1272**. The cap **1284** includes circumferentially spaced fingers **1288** spaced about the threaded bore **1286**. With reference to FIG. **105**, the carriage **1274** defines circumferentially spaced slots **1290**. The fingers **1288** and the slots **1290** are engaged in alternating arrangement circumferentially about the lead screw **1272**. The fingers **1288** of the cap **1284** engage the slots **1290** circumferentially about the lead screw **1272** to prevent relative rotation and slidingly engage each other axially along the lead screw **1272** to allow for relative translation along the lead screw **1272**. As such, the cap **1284** can slide along and relative to the carriage **1274** axially along the lead screw **1272**.

A spring element **1292** is disposed between the cap **1284** and the lead screw **1272**. Spring element **1292** extends axially along the lead screw **1272** between the cap **1284** and the lead screw **1272**. The spring element **1292** can be an O-ring of elastomeric material but alternatively can be any type of suitable spring element without departing from the nature of the present invention. The spring element **1292** exerts pressure on the carriage **1274** axially along the lead screw **1272** to bias the threads of the threaded bores **1280** of the carriage **1274** against the threads of the threaded surface **1278** of the lead screw **1272**, which limits backlash during changes in rotational direction of the lead screws **1272** relative to the carriage **1274**.

With reference to FIG. **101**, the carriages **1274** of the yaw adjustment device **1268** and the pitch adjustment device **1270** each define a slot **1294**. The slots **1294** extend in perpendicular directions and intersect at a pocket **1296**. As best shown in FIG. **96**, the casing **1208** of the distal assembly **1202** includes a post **1298** that extends into the pocket **1296**.

With reference to FIGS. **102** and **103**, the slots **1294** are rounded or arcuate in cross-section. As best shown in FIGS. **96**, **102**, and **104**, a connecting member **1257** is engaged with each slot **1294** and the post **1298**. Specifically, each connecting member **1257** is shaped like gimbal **1258** and defines an opening **1259** receiving the post **1298**. The post **1298**, the slots **1294**, and the opening **1259** of the connecting member **1257** each typically include a surface formed of a low friction material such as, for example, stainless steel, brass, or bronze, and is typically highly polished. The outer surface of connecting member **1257** can pivot relative to the arcuate inner surface of slots **1294**.

With reference to FIGS. **102** and **104**, the connecting members **1257** each have a thickness T that is less than a width W of the slots **1294** and the connecting members **1257** each have a height H greater than the width W of the slots **1294**. As such, the connecting members **1257** are introduced to the slots **1294** in an orientation such that the thickness T of the connecting member **1257** fits within the width W of the slot **1294**. The connecting member **1257** is then rotated to the position shown in FIGS. **96** and **97** to engage the connecting member **1257** in the slot **1294**. When engaged in the opening **1259**, the post **1298** prevents rotation of the connecting member **1257** to a position of disengagement from the slots **1294**.

With reference to FIG. **100**, a yaw motor **1302** is engaged with the lead screws **1272** of the yaw adjustment device **1268** and a pitch motor **1304** is engaged with the lead screws **1272** of the pitch adjustment device **1270**. The yaw motor **1302** and the pitch motor **1304** are connected to respective motor controllers **232**, **234**, which are connected to the power source **140** shown in FIG. **1** and described above. The motor controllers **232**, **234** are typically disposed remotely from the instrument **1200**.

A yaw gear set **1306** engages the yaw motor **1302** and the lead screws **1272** of the yaw adjustment device **1268**. A pitch gear set **1308** engages the pitch motor **1304** and the lead screws **1272** of the pitch adjustment device **1270**. The lead screws **1272** of the yaw adjustment device **1268** and the pitch adjustment device **1270** engages gears (not individually numbered) of the gear sets **1306**, **1308**, respectively, with a press-fit engagement and/or by engagement with keyed ends, e.g., hexagonally shaped ends. The outer casing **1206** of the proximal assembly **1204** houses the yaw motor **1302** and yaw gear set **1306** and houses the pitch motor **1304** and the pitch gear set **1308**.

Yaw gear set **1306** is arranged to simultaneously rotate both lead screws **1272** of the yaw adjustment device **1268** at the same speed and angle upon actuation of the yaw motor **1302**. Pitch gear set **1308** is arranged to simultaneously rotate both lead screws **1272** of the pitch adjustment device **1270** at the same speed and angle upon actuation of the pitch motor **1304**. As such, the carriage **1274** for each respective adjustment device smoothly moves along the lead screws **1272** as the lead screws **1272** are rotated.

To adjust the yaw of the distal assembly **1202** relative to the proximal assembly **1204**, the yaw motor **1302** rotates the yaw gear set **1306**, which in turn rotates the lead screws **1272** and moves the carriage **1274** of the yaw adjustment device **1268** relative to the frame **1266** of the adjustment assembly **1264**. As the carriage **1274** of the yaw adjustment device **1268** moves relative to the frame **1266**, the carriage **1274** moves the post **1298**, which pivots the casing **1208** about the gimbal **1258** to adjust the yaw of the distal assembly **1202** and the cutting accessory **202** mounted to the distal assembly **1202**.

To adjust the pitch of the distal assembly **1202** relative to the proximal assembly **1204**, the pitch motor **1304** rotates the pitch gear set **1308**, which in turn rotates the lead screws **1272** and moves the carriage **1274** of the pitch adjustment device **1270** relative to the frame **1266** of the adjustment assembly **1264**. As the carriage **1274** of the pitch adjustment device **1270** moves relative to the frame **1266**, the carriage **1274** moves the post **1298**, which pivots the casing **1208** about the gimbal **1258** to adjust the pitch of the distal assembly **1202** and the cutting accessory **202** mounted to the distal assembly **1202**. The connecting member **1257** move along the slot **1294** when the carriage **1274** moves the post **1298**.

Yaw motor **1302** and the pitch motor **1304** can be operated simultaneously and/or independently to adjust the yaw and the pitch of the distal assembly **1202** relative to the proximal assembly **1204**. The lead screw motor **1240**, as discussed above, can be operated simultaneously with the yaw motor **1302** and/or the pitch motor **1304** to simultaneously move the cutting accessory along the longitudinal axis A and adjust the yaw and/or pitch of the distal assembly **1202** relative to the proximal assembly **1204**. The lead screw motor **1240** can also be operated independently from the yaw motor **1302** and the pitch motor **1304**.

As shown in FIG. **74**, at least one circuit board **1263** is mounted in the outer casing **1206**. Position sensors for the longitudinal axis A position (e.g., magnet **1255** and magnet sensor), yaw position, and pitch position of the cutting accessory **202** are in communication with the circuit board **1263**. For example, flex circuits connect the position sensors to the circuit board **1263**.

In one embodiment, a trigger or foot pedal, or alternatively a button, (not shown) can be supported by the outer casing **1206** of the proximal assembly **1204** to power the accessory motor, i.e., to selectively supply power to or not supply power to the cutting accessory **202**. As set forth above with respect to instrument **200**, the instrument **1200** can include a sensor (not identified) disposed inside the instrument **1200**. The sensor generates a signal if the trigger is actuated and/or not actuated. The output signals from the sensor are forwarded by the data connection **133** to the instrument driver **130**. Based on the state of this sensor signal, the instrument driver **130** applies energization signals to the drive motor **1212** when the tip or bur head **204** of the cutting accessory **202** is in the boundary **106** of target volume **104**. In the alternative to, or in addition to the trigger or button, a foot pedal (not shown) can be in communication with the instrument **1200** to control the drive motor **1212** by providing on/off instructions to the drive motor **1212**. As set forth above, the rotational speed of the accessory **202** is also dependent upon the position of the tip or bur head **204** of the accessory **202** relative to the "home" position.

As set forth above, when the tip or bur head **204** of the cutting accessory **202** is outside of the boundary **106** of the target volume **104**, the instrument driver **130** does not apply an energization signal to the drive motor **1212** even if the trigger is actuated. The tracking and control system **100** can be configured such that the instrument driver **130** applies an energization signal to reduce the speed of the cutting accessory **202** when the tip or bur head **204** of the cutting accessory **202** enters the buffer **105** of the target volume **104**, which is best shown in FIG. **2**.

IX. Display Screen

A display screen **1402**, also referred to as display **1402**, is in communication with the surgical instrument **200**, **1200** and provides instructions to the user for proper location and orientation of the surgical instrument **200**, **1200** to locate and orientate the cutting accessory **202** in the work boundary **106**. As set forth above, the display **1402** is in communication with the navigation system for indicating the position of the working portion relative to the work boundary **106**.

As set forth above, the surgical instrument **200**, **1200** adjusts the accessory **202** about three degrees of freedom within an adjustment range (not identified in the Figures) to orientate the accessory **202** in the work boundary **106**. The display screen **1402** can be selectively used by the user. For example, the use of the display screen **1402** may be required for applications requiring more than three degrees of freedom of tip positioning and can be optional for applications requiring three or less degrees of freedom of tip positioning.

As set forth above, the tracking and control system **100** tracks the positions and orientations of the anatomy and the surgical instrument **1200** to keep the tip or bur head **204** of the cutting accessory **202** within the target volume **104**. Based on the tracking of the positions and orientations of the anatomy and the surgical instrument **1200** by the tracking and control system **100**, the display screen **1402** indicates adjustments, if any, that are required to locate and orientate the handle assembly **500** of the surgical instrument **200** or the outer casing **1206** of the surgical instrument **1200** such that the work boundary **106** is within the adjustment range of the surgical instrument **200**, **1200**, i.e., such that the surgical instrument is capable of adjusting to locate and orientate the cutting accessory **202** in the work boundary **106**.

Display screen **1402** can, for example, be a liquid crystal display (LCD) monitor, a light emitting diode (LED) monitor, an organic light emitting diode (OLED) monitor, etc., however, it is appreciated that the display screen **1402** can be any type of digital or analog display without departing from the nature of the present invention. The display screen **1402** can be mounted to the surgical instrument **200**, **1200** and, more specifically, can be mounted to be generally along the line of vision of the user when viewing the cutting accessory **202**, as shown in FIGS. **72** and **73**, for example. Alternatively, the display screen **1402** can be spaced from and independently movable relative to the surgical instrument **200**, **1200**.

Various embodiments of visual content of the display screen **1402** are shown in FIGS. **107-111**. The display screen **1402** can display a target reticle **1404** including cross-hairs **1406** and concentric circles **1408**. The intersection **1414** of the cross-hairs identifies the desired location and/or orientation of the handle assembly **500** of surgical instrument **200** or the outer casing **1206** of surgical instrument **1200**.

As shown in FIGS. **108**, **110**, and **111**, display screen **1402** can display a translation legend **1410** and an associated translation marker **1412**. Translation of the handle assembly **500** of the surgical instrument **200** or the outer casing **1206** of surgical instrument **1200** relative to the target volume **104** can be mirrored by movement of the translation marker **1412** on the display screen **1402**. In other words, the translation marker **1412** moves to the left on the display screen **1402** in response to translation of the handle assembly **500** or the outer casing **1206** to the right, and the translation marker **1412** moves to the right on the display screen **1402** in response to translation of the handle assembly **500** or the outer casing **1206** the left. Similarly, the translation marker **1412** moves up or down on the display screen **1402** in response to translation of the handle assembly **500** or the outer casing **1206** down or up, respectively. As such, to properly locate the cutting accessory **202** relative to the target volume **104**, the user translates the handle assembly **500** or the outer casing **1206** such that the intersection **1414** of the cross-hairs moves toward the translation marker **1412**. It is appreciated that the scale on the display screen **1402** can be increased or decreased. In other words, translation of the translation marker **1412** on the display screen **1402** can be a different scale in comparison to actual translation of the handle assembly **500** or outer casing **1206**.

When used with the target reticle **1404**, for example, the user initially translates the handle assembly **500** or the outer casing **1206** left/right and/or up/down to locate the intersection **1414** of the cross-hairs **1406** at the translation marker **1412**, which locates the cutting accessory **202** within the work boundary **106**. Depending upon the surgical procedure, the cutting accessory **202** may be powered when the handle assembly **500** or outer casing **1206** is moved such that the translation marker **1412** moves away from the intersection **1414** of the cross-hairs **1406** but remains in the boundary **106**. Alternatively, in other surgical procedures, such as drilling in preparation for insertion of a screw or pin, the cutting accessory **202** may only be powered when the intersection **1414** of the cross-hairs **1406** is aligned with the translation marker **1412** or the inner circle of the concentric circles **1408**.

In some embodiments, the display screen **1402** indicates the deviation of the working portion relative to the home position. The translation marker **1412** indicates the deviation of the accessory distal tip or bur head **204** from home position. In this embodiment, the user can adjust the pitch, yaw, and translation along the longitudinal axis A to keep the cutting tip **204** on a path or trajectory as long as the tip or bur head **204** is not beyond the adjustment envelope, i.e., not beyond the constraints of pitch/yaw/z-axis adjustment from home position. As a result, the user only needs to maintain the translation marker **1412** within a certain range from center, which is dependent on the extent of deviation from home to which the instrument is capable.

As shown in FIGS. **107-109**, the display screen **1402** can display an orientation legend **1416** and an associated orientation marker **1418**. The orientation legend **1416** and orientation marker **1418** display the orientation, i.e., the pitch and yaw, of the handle assembly **500** or the outer casing **1206** relative to the target volume **104**. Orientation of the handle assembly **500** or the outer casing **1206** can be schematically mirrored by movement of the orientation marker **1418** on the display screen **1402**. Specifically, the orientation marker **1418** moves to the left or to the right on the display screen **1402** in response to yaw of the handle assembly **500** or the outer casing **1206** to the right or to the left, respectively, relative to the target volume **104**. The orientation marker **1418** moves up or down on the display screen **1402** in response to pitch of the handle assembly **500** or the outer casing **1206** down or up, respectively, relative to the target volume **104**. As such, to properly orientate the cutting accessory **202** relative to the target volume **104**, the user moves the handle assembly **500** or the outer casing **1206** such that the intersection **1414** of the cross-hairs **1406** moves toward the orientation marker **1418**.

The spacing between the circles **1408** can be a non-linear representation of the angular movement required to properly orientate the proximal assembly **1204** relative to the target volume **104**. For example, when the orientation marker **1418** is on the innermost ring, the required movement of the handle assembly **500** or the outer casing **1206** is 1°, when the orientation marker **1418** is on the next ring, the required movement of the handle assembly **500** or the outer casing **1206** is 5°, and when the orientation marker **1418** is on the next ring, the required movement of the handle assembly **500** or the outer casing **1206** is 25°. The values associated with each ring can be adjusted.

When used with the target reticle **1404**, for example, the user initially orientates the handle assembly **500** or the outer casing **1206** to locate the intersection **1414** of the cross-hairs **1406** at the orientation marker **1418**, which orientates the cutting accessory **202** within the work boundary **106**.

Depending upon the surgical procedure, the cutting accessory **202** may be powered when the handle assembly **500** or outer casing **1206** is moved such that the orientation marker **1418** moves away from the intersection **1414** of the cross-hairs **1406** but the tip or bur head **204** remains in the work boundary **106** of the target volume **104** or within a predetermined deviation from the boundary **106**, such as when the boundary **106** is a predefined trajectory. Alternatively, in other surgical procedures, such as drilling in preparation for insertion of a screw or pin, the cutting accessory **202** may only be powered when the intersection **1414** of the cross-hairs **1406** is aligned with the orientation marker **1418** or the inner circle of the concentric circles **1408**.

With reference to FIG. **109**, the target reticle **1404** can include an acceptance ring **1420**. The acceptance ring **1420**, which can be the innermost of the concentric circles **1408** of the target reticle **1404**, can be of a different color and/or thickness than the other concentric circles **1408** for identification purposes.

The acceptance ring **1420** can indicate the range of positions of the nose tube **1218** in which the cutting accessory **202** can be operated. The acceptance ring **1420** is typically used with the orientation marker **1418**. In other words, the cutting accessory **202** can be operated when the orientation marker **1418** is in the acceptance ring **1420**.

The control system **100** can be configured to control the display **1402** to change a resolution of the display **1402** as the working portion approaches the virtual boundary. In other words, the acceptance ring **1420** can, for example, change during a procedure. For example, during a drilling procedure to create a hole for a pedicle screw, the acceptable pitch and yaw position of the nose tube **1218** can change as the tip or bur head **204** of the cutting accessory **202** moves deeper into the bone, i.e., the acceptable pitch and yaw position decreases to avoid collision between the nose tube **1218** and the side of the hole as the hole gets deeper. In such a procedure, the acceptance ring **1420** can be configured to become smaller as the tip or bur head **202** moves deeper into the bone **102** to indicate that the amount of acceptable deviation in the pitch and yaw directions is decreasing.

Display screen **1402** can display a depth legend **1422** and an associated depth marker **1424**. The depth legend **1422** and the depth marker **1424** display the depth of the tip or bur head **204** of the cutting accessory **202** relative to the target volume **104**.

In one embodiment, the depth legend **1422** includes a top limit line **1426**, a bottom limit line **1428**, and a middle line **1430**. The top limit line **1426**, which is the top line on the depth legend **1422** in FIGS. **107-109**, indicates the surface of the target volume **104** and the bottom limit line **1428**, which is the bottom line on the depth legend **1422** in FIGS. **126-128** and **131**, indicates the bottom of the target volume **104**. In other words, the depth legend **1422** and the depth marker **1424** indicate that the tip or bur head **204** of the cutting accessory **202** is at the surface of the target volume **104** when the depth marker **1424** is located on the top limit line **1426**. The depth legend **1422** and the depth marker **1424** indicate that the tip or bur head **204** of the cutting accessory **202** is at the bottom of the target volume **104** when the depth marker **1424** is located on the bottom limit line **1428**.

In another embodiment, the middle line **1430** indicates a home position of the tip or bur head **204**. To locate the bur head **204** of the cutting accessory **202** at the correct depth relative to the target volume **104**, the user moves the handle assembly **500** or the outer casing **1206** such that the middle line **1430** of the depth legend **1422** is displayed about the depth marker **1424**.

As shown in FIGS. **107-109**, depth legend **1422** can display an extension **1432** that extends upwardly from the top limit line **1426**. The extension **1432** indicates the area immediately adjacent the target volume **104**.

As shown in FIG. **110**, the display screen **1402** can display an acceptance bar **1434**, which is shown adjacent the depth legend **1422** in FIG. **110**. In the alternative in which the top limit line **1426** indicates the surface of the target volume **104** and the bottom limit line **1428** indicate the bottom of the target volume **104**, the acceptance bar **1434** shown in FIG. **110** includes a top **1436** that indicates the surface of the target volume **104** and a bottom **1438** that indicates the bottom of the target volume **104**.

The display screen **1402** displays a top banner **1440** and a bottom banner **1442**, each of which can display selected information. For example, the top banner **1440** and/or the bottom banner **1442** can display the type of procedure being performed, patient information, etc. The top banner **1440** and/or the bottom banner **1442** can include indicators **1444** that indicate blocked visibility of the trackers **114**, **116**. The indicators **1444** can be color coded (e.g., red and green) to indicate whether visibility is established or not established.

Translation legend **1410**/translation marker **1412**, orientation legend **1416**/orientation marker **1418**, and depth legend **1422**/depth marker **1424** can be independently displayed or hidden on the display screen **1402**. The translation marker **1412**, the orientation marker **1418**, and the depth marker **1424** can each be of a different color for ease of differentiation. The translation legend **1410**, the orientation legend **1416**, and the depth legend **1422** can be colored the same color as the translation marker **1412**, the orientation marker **1418**, and the depth marker **1424**, respectively, for easy identification. In addition to or in the alternative to color coding, the translation marker **1412**, the orientation marker **1418**, and the depth marker **1424** can each be a different symbol for ease of differentiation.

FIGS. **107-111** show various embodiments of visual content of the display screen **1402**. The display screen **1402** shown in FIG. **109** displays the orientation legend **1416** and orientation marker **1418** and displays the depth legend **1422** and depth marker **1424**. As set forth above, to properly orientate the cutting accessory **202** relative to the target volume **104**, the user moves the handle assembly **500** or the outer casing **1206** such that the intersection **1414** of the cross-hairs **1406** moves toward the orientation marker **1418**. As such, in the scenario shown in FIG. **107**, the user adjusts the yaw of the handle assembly **500** or outer casing **1206** to the right and pitches the handle assembly **500** or outer casing **1206** downwardly to align the intersection **1414** with the orientation marker **1418**. To locate the tip or bur head **204** of the cutting accessory **202** at the correct depth relative to the target volume **104**, the user moves the handle assembly **500** or the outer casing **1206** such that the bottom line **1428** of the depth legend **1422** is disposed on the depth marker **1424**. For example, the bottom line **1428** moves toward the depth marker **1424** when drilling into bone with a bur to create a bore for a pedicle screw or pin.

Display screen **1402** shown in FIG. **107** displays the acceptance ring **1420** and as such, the cutting accessory **202** can be powered when the acceptance ring **1420** is displayed about the orientation marker **1418**. Alternatively, the display screen **1402** shown in FIG. **109** does not display an acceptance ring. Display screen **1402** shown in FIG. **108** displays the translation legend **1410** and translation marker **1412**, the orientation axis and orientation marker **1418**, and the depth legend **1422** and the depth marker **1424**. In this scenario, the user adjusts the yaw of the handle assembly **500** or outer casing **1206** to the right and pitches the handle assembly **500** or outer casing **1206** downwardly to align the intersection **1414** with the orientation marker **1418**. The user also translates the handle assembly **500** or outer casing **1206** upwardly and to the left to align the intersection **1414** with the translation marker **1412**. To locate the tip or bur head **204** of the cutting accessory **202** at the correct depth relative to the target volume **104**, the user moves the handle assembly **500** or the outer casing **1206**. The display screen **1402** shown in FIG. **108** displays the acceptance ring **1420** and as such, the cutting accessory **202** can be powered when the acceptance ring **1420** is disposed about the orientation marker **1418**.

Display screen **1402** shown in FIG. **108** displays the translation legend **1410** and translation marker **1412** and displays the depth legend **1422** and depth marker **1424**. In this scenario, the user translates the handle assembly **500** or outer casing **1206** upwardly and to the left to align the intersection **1414** with the translation marker **1412**, and more preferably align the intersection **1414** with the translation marker **1412**. As set forth above, the display screen **1402** of FIG. **110** displays an acceptance bar **1434**. In FIG. **110**, the user locates the tip or bur head **204** of the cutting accessory **202** at the proper depth by moving the tip or bur head **204** deeper into the target volume **104** until the acceptance bar **1434** is displayed along the depth marker **1424**.

Although not shown, it should be appreciated that display screen **1402** can be blank, i.e., does not display the target reticle **1404** and does not include any direction legends or markers. Such an embodiment can be used for cutting applications that do not require additional guidance from the display screen **1420**.

The display screen **1402** shown in FIG. **111** displays the translation legend **1410** and translation marker **1412** and displays the depth legend **1422** and depth marker **1424**. In this scenario, the user translates the handle assembly **500** or outer casing **1206** upwardly and to the left to align the intersection **1414** with the translation marker **1412**. With continued reference to FIG. **111**, the user locates the bur head **204** of the cutting accessory **202** at the proper depth by moving the bur head **204** out of the target volume **104** until the middle line **1430** is aligned with the depth marker **1424**.

X. Surgical Procedures

Several surgical procedures can be carried out by the system **100** and instruments **200**, **1200**. Some of these procedures involve the removal of tissue such as bone. Removal of bone with the instruments **200**, **1200** can include sculpting, shaving, coring, boring, or any other method of removing bone, depending on the procedure and the type of cutting accessory **202** attached to the instrument **200**, **1200**. The instrument **200**, **1200** can be used to remove tissue in spine, knee, hip, cranium, and other procedures. These procedures may be open procedures or minimally invasive procedures.

During each surgical procedure, positions and/or orientations of the bur head **204** of the instrument **200**, **1200** and the anatomy being treated are dynamically tracked. Representations of the bur head **204** and the anatomy are continuously shown on the displays **113**, **1402** so that the surgeon is always aware of their relative position. The position of the bur head **204** is controlled by the system **100** based on the relationship of the bur head **204** to boundaries defined in the system **100**, as previously described. In some cases, the boundaries define areas of the anatomy to avoid and in other cases, the boundaries define paths that the bur head **204** is specifically controlled by the system **100** to traverse.

Referring to FIGS. **112**A through **112**D, in one procedure, the instrument **200**, **1200** is used to perform a spinal fusion. Spinal fusion procedures in which the instrument **200**, **1200** can be employed to remove tissue include, but are not limited to, an ALIF (anterior lumbar interbody fusion), PLIF (posterior lumbar interbody fusion), TLIF (transforamenal lumbar interbody fusion), DLIF (direct lateral interbody fusion), or XLIF (extreme lateral interbody fusion).

Referring to FIG. **112**A, in some interbody spinal fusions, the instrument **200**, **1200** may be used to first cut and penetrate through bone to access a patient's intervertebral disc **1600**. For instance, posterior access to the disc **1600** may require penetration through the lamina **1602**. Depending on the approach taken by the surgeon, total or partial removal of the lamina **1602** of a patient may be required to access the disc **1600**. In these embodiments, the bur head **204** (e.g., tip) of the cutting accessory **202** penetrates into the patient's lamina **1602** to remove all or portions of the lamina **1602**.

Still referring to FIG. **112**A, once the bone has been cut away to gain access to the disc **1600**, the instrument **200**, **1200** can also perform a discectomy by cutting away all or part of the patient's disc **1600**.

In some cases, it is not required to first remove bone to perform the discectomy. Whether bone is required to be cut to access the disc **1600** depends on the surgeon's entry decision for the procedure, e.g., whether ALIF, PLIF, TLIF, DLIF, etc. The portions of the lamina **1602** and the disc **1600** to be removed can be pre-operatively defined as boundaries stored in the system **100** to control movement of the bur head **204**.

Positions and orientations of the vertebral bodies involved in the procedure, including their end plates **1604**, **1606**, and the disc **1600** are tracked using navigation by attaching a tracker **1612** to each of the vertebral bodies and then matching the vertebral bodies to pre-operative images so that the surgeon can visualize the material being removed on the display **113**, **1402**. The position and orientation of the disc **1600** can be inferred by tracking the position and orientation of the bone above and below the disc **1600**. Portions of bone or disc to be removed can be displayed in one color, while the material to remain can be displayed in a different color. The display is updated as cutting progresses to show the material still to be removed while eliminating the material already removed. In some embodiments, each tracker includes three or more active or passive markers **1614** for tracking movement of the vertebral bodies.

Techniques for registering pre-operative images to a patient's anatomy are well known in the surgical navigation arts. In some embodiments, a tracked pointer, such as that shown in U.S. Pat. No. 7,725,162, entitled "Surgery System", the disclosure of which is hereby incorporated by reference, is used to identify anatomical landmarks on each vertebral body, which are then matched to the pre-operative image to register the pre-operative image to the anatomy.

Referring to FIG. **112**B, bone from bone plates **1604**, **1606** can also be removed by the bur head **204** to expose bleeding spongy bone. The exposure of bleeding bone promotes bone ingrowth with bone matrix material **1608**.

The surfaces of the end plates **1604**, **1606** can be cut to a surgeon's shape preference. The end plates **1604**, **1606** are shaped by the bur head **204** under the guidance of the tracking and control system **100** to create the desired shapes. The desired shape is predefined as a boundary in the system **100** so that the bur head **204** is controlled to stay within the boundary. In some cases, the desired shape is a planar surface milled into the end plates **1604**, **1606**, while in other cases, ribbed, undulating, rough, or other non-flat surfaces are preferred to further lock the implant **1610** (FIG. **112**C) in position.

After preparing the end plates **1604**, **1606**, the implant **1610** is positioned between the end plates **1604**, **1606**. The bone matrix material **1608** can be placed in the disc space and inside the implant **1610** before and/or after placement of the implant **1610**, depending on the type and size of implant being used and its location. The bone matrix material **1608** can include autograft or allograft materials with or without bone morphogenetic proteins (BMPs). The bone growth matrix **1608** could be placed into the disc space by forceps, cannula and plunger, or the like. FIG. **112**C shows the implant **1610** in position with bone matrix material **1608** located in the disc space anterior to the implant **1610** and inside the implant **1610**.

The implant **1610** shown has ribs **1616** defining upper and lower surfaces of the implant **1610**. A boundary could be defined in the system **100** so that the end plates **1604**, **1606** are milled to provide recesses (not numbered) to accommodate the ribs **1616** and further lock the implant **1610** in position.

Referring to FIG. **112**D, once the implant **1610** is positioned between the end plates **1604**, **1606**, the bur head **204** of the instrument **200**, **1200** could be used to prepare pilot holes **1618** in the pedicles. The pilot holes **1618** are created to receive pedicle screws **1620** that form part of a screw/rod fixation system used to stabilize the implant **1610**.

Separate boundaries define trajectories for the pilot holes. The system **100** controls the bur head **204** to stay along the trajectories as previously described to accurately cut the pilot holes **1618**, including direction and depth. The screws **1620** are placed into the pilot holes **1618** with a screw driving tool (not shown). The screws **1620** are secured with an appropriate rod **1622**.

In other embodiments, such as in anterior or lateral procedures, screws are used in conjunction with bone plates to provide fixation for the implants.

During spinal fusion procedures, additional boundaries (not shown) can be defined in the system **100** to indicate locations of sensitive anatomy that needs to be avoided by the bur head **204**. By defining these boundaries in the system **100**, they can be avoided by navigation of the instrument **200**, **1200**. When the bur head **204** approaches such boundaries, the bur head **204** can be diverted away in three degrees of freedom movement as described above. Additionally, the surgeon can visualize the boundaries defining the sensitive anatomy on the display **113**, **1402**. The sensitive anatomy may include the aorta and/or vena cava of the patient or any vasculature and/or nerves of the patient.

Other spine procedures in which the instrument **200**, **1200** may be employed include any procedures involving stenosis, vertebral body replacement, or scar tissue removal. In the spinal procedures discussed, the bone of interest can be accessed either with an open procedure in which the tissue in cut and laid open, or in a minimally invasive procedure in which the bur head **204** is placed at the site in bone through a lumen of a guide tube, cannula or other access channel.

Referring to FIGS. **113**A and **113**B, another procedure that can be carried out by the instrument **200**, **1200** is femoral acetabular impingement (FAI) surgery. FAI can occur when an excess amount of bone is present on the femoral head of a patient. The excess bone is usually located along an upper surface of the femoral head and creates a cam-shaped head. Due to its shape, i.e., non-spherical, rotation of the femoral head in a normally shaped socket results in impingement. See, for example, the impingement shown in FIG. **113**A. To alleviate this impingement, the bur head **204** of the instrument **200**, **1200** removes the excess bone to create a more uniform femoral head and relieve the area of impingement. The instrument **200**, **1200** can also be used in some embodiments to shape bone of the acetabulum or labram attached to the acetabulum if desired.

Before the FAI procedure begins, planning involves preoperative scans, e.g., MRI or CT scans, to provide 3-D images of the femur **1640** and hip **1642**. These images are stored in the system **100**. Boundaries defining the volume of excess bone **1641** to be removed and/or portions of anatomy to remain (such as the acetabulum) are then defined either automatically by the system **100** based on a dynamic simulation of hip movement or by the surgeon. The boundaries are stored in the system **100** and later used to control movement of the bur head **204** in three degrees of freedom to maintain the desired relationship between the bur head **204** and the boundaries.

Trackers **1644** with active or passive markers **1646** are mounted to the femur **1640** and hip **1642**. The trackers **1644** may be fixed to the femur **1640** and hip **1642** using bone pins inserted into bone through the skin, or other methods known to those skilled in the art.

The pre-operative images are registered to the anatomy using the trackers **1644** and pointer as previously described so that the system **100** can track movement of the bur head **204** (e.g., tip) relative to the femur **1640** and the hip **1642**. In particular, the position and orientation of the femoral head **1648** and acetabulum **1650** are tracked during the procedure.

In a next step of the procedure, two separate access paths are created through the patient's skin. One path is created for the bur head **204** of the instrument **200**, **1200** and one path is created for an endoscope (not shown). These access paths can be provided by guide tube, cannula, or other access creation device. In certain embodiments, these access devices can be tracked with the system **100** by attaching a tracker (not shown) to the devices. This allows the system **100** or user to establish the correct path to the acetabulum/hip joint.

The instrument **200**, **1200** is then placed through one access path. The instrument **200**, **1200** is operated to remove away the desired volume of excess bone **1641** from the femoral head **1648**. The trackers **1644** are used by the system **100** to monitor the location of the bur head **204** relative to the femoral head **1648**, acetabulum, and any defined boundaries associated therewith. The instrument **200**, **1200** is then controlled by the system **100** which moves the bur head **204**, if necessary, to avoid tissue that is to remain and to ensure only the cutting of material that is to be removed. This ensures that only the desired volume of the material **1641** is removed from the femoral head **1648** to relieve the impingement.

In this procedure, when bone is being removed, the hip may need to be retracted to access difficult to reach areas of the femoral head **1648**. In the autonomous mode the system **100** may first prompt for moving the patient and retracting the hip to access these other areas.

During the procedure, the surgeon can view the volume of bone on the femoral head **1648** to be removed, which can be indicated on the display **113**, **1402** in a different color than the bone to remain. The display **113**, **1402** can also show the bone remaining to be removed relative to the boundary defining the desired final shape of the femoral head **1648**. By tracking the bur head **204**, the femoral head **1648**, and the acetabulum **1650**, the position of the bur head **204** relative to the boundary and the anatomy can be shown on the display **113**, **1402** thereby giving the surgeon confidence that a properly shaped femoral head **1648** remains after the procedure.

A representation of the bone on the femoral head **1648** remaining to be removed, as well as the desired final shape of the femoral head can be overlayed onto a viewing station associated with the endoscope (not shown). In this manner, the display for the endoscope also dynamically shows the bone being removed along with the endoscopic views of the bone and other tissues. In this embodiment, a tracking device (not shown) is also attached to the endoscope (not shown) so that the position and orientation of the endoscope can be determined in the same coordinate system as the anatomy and the instrument **200**, **1200**.

The system **100** can be programmed so that as bone is removed, the dynamic simulator of hip movement estimates the amount of impingement relieved or remaining. For instance, at the start of the procedure, the amount of free rotation (i.e., rotation with no impingement) of the femoral head **1648** in the acetabulum **1650** may be X degrees. As the procedure progresses the value of X increases. This value can be displayed on the display **113**, **1402**. The system **100** may alert the surgeon when the value of X reaches a predetermined threshold, indicating that enough bone material has been removed.

In some embodiments, other materials may be removed by the bur head **204**. For example, the bur head **204** can be used to debride chondral lesions or labral, excise bony prominences and/or reshape the acetabular rim.

Referring to FIG. **114**, another procedure performed by the system **100** and instrument **200**, **1200** is anterior cruciate ligament (ACL) repair. In ACL repair, access to the knee is provided by an arthoscope (not shown) or other guide tube or cannula. The existing ACL is first removed using a shaver or other device. A graft **1651** is then created to replace the removed ACL. Suitable grafts include a semi-tendonosis/gracilis graft or bone-tendon-bone (BTB) graft.

Prior to the ACL repair, a pre-operative image, such as an MRI or CT scan can be used to create a three dimensional model of the knee joint, including femur **1656** and tibia **1658** and ACL. Tracking devices **1660** with active or passive markers **1662** are mounted to each of the femur **1656** and tibia **1658** using conventional methods, for purposes of tracking positions and orientations of the femur **1656** and tibia **1658** during the procedure and for registering the pre-operative image to the anatomy as previously described.

During the procedure, two tunnels or passages **1652**, **1654** are made in the femur **1656** and tibia **1658**, respectively, in which the graft **1651** is secured. Traditionally, the passages **1652**, **1654** are made separately from different approaches to the femur **1656** and tibia **1658**, thus requiring two separate cutting guides. For instance, in a typical procedure, the tibia **1658** is approached from beneath the joint and the tunnel is then drilled toward the joint. The femur **1656** is drilled by starting in the joint and then drilling away from the joint into the femur **1656**. The instrument **200**, **1200** can be used in the same traditional manner, without any cutting guides.

In the embodiment of FIG. **114**, boundaries can be established in the system **100** that define the passages **1652**, **1654**. By tracking the positions of the bur head **204**, femur **1656** and tibia **1658** the system **100** can control movement of the bur head **204** (e.g., tip) to stay within the boundaries. Since the boundaries are tied to the anatomy, tracking movement of the anatomy also tracks movement of the boundaries.

Using the tracking and control system **100**, instead of two, separate, discontinuously-created paths in the femur **1656** and tibia **1658** as described above, continuously-formed passages can be created starting from outside of the knee joint, through the tibia **1658**, into the knee joint, and then into the femur **1656**. The passages can also be created starting from outside of the knee joint, through the femur **1656**, into the knee joint, and then into the tibia **1658**.

To facilitate continuously-formed passages, the virtual boundary defining the passage **1652** in the femur **1656** can be aligned with the virtual boundary defining the passage **1654** in the tibia **1658**. For instance, the passage **1654** in the tibia **1658** can first be made and then, without removing the cutting accessory **202** from the tibia passage **1654**, the virtual boundary defining the femur passage **1652** can be aligned with the tibia passage **1654** (or its virtual boundary). This can be done by tracking the femur **1656** and the tibia **1658** and providing an indication of the passage or boundary alignment (or misalignment) on the display **113**, **1402**. The value of alignment can be established as degrees from alignment or similar values that can also be displayed numerically or graphically on the display **113**, **1402**. The procedure can also be carried out by cutting first in the femur **1656** and then proceeding to the tibia **1658**.

When the passages **1652**, **1654** are aligned, the display **113**, **1402** may provide an audible or visual indication so that the surgeon may operate the instrument **200**, **1200** to further penetrate the bur head **204** into the femur **1656** to complete the cutting. The surgeon continues as long as the alignment is maintained. The result is forming the passages **1652**, **1654** in one continuous direction without removing bur head tip **204** from the first formed passage and without any cutting guides.

Once the passages **1652**, **1654** are created, the graft **1651** is passed through ACL placement instruments into the passages **1652**, **1654**. The graft **1651** is then fixed inside the passages **1652**, **1654** with screws, pins, or the like.

Referring to FIGS. **115**A and **115**B, another procedure in which the system **100** and instruments **200**, **1200** can be employed is the repair of focal cartilage defects. One such procedure is arthroscopic microfracture surgery (AMS). AMS is used to repair cartilage **1670** on an articular surface that has worn away exposing bone **1674**. The exposed bone, being on an articular surface, is often load bearing and can result in pain to the patient. Often AMS is employed on the articular surfaces of a knee joint, particularly, a femur **1672**.

Prior to the AMS, a pre-operative image, such as an MRI or CT scan can be used to create a three dimensional model of the femur **1672** (and tibia if needed). Tracking devices **1676** with active or passive markers **1678** are mounted to each of the femur **1672** and tibia (if tracked) using conventional methods, for purposes of tracking the femur **1672** and tibia during the procedure and for registering the pre-operative image to the anatomy as previously described.

During the procedure, the worn away area of the bone **1674** and surrounding cartilage **1670** is accessed by an arthroscope, cannula, or other guide tube placed through the skin of the patient that provides an access path to the worn away area of the bone **1674**. The bur head **204** of the instrument **200**, **1200** is then placed through the created access path into proximity of the bone **1674**. The worn away area of bone **1674** is then reshaped by the bur head **204** (e.g., tip) to smooth any rough edges of the remaining cartilage **1670** surrounding the bone **1674**. The exposed bone **1674** is also smoothed by the bur head **204** to a contour resembling that of the original cartilage **1670** that was worn away.

A boundary can be established in the system **100** that defines the reshaped volume as shown in FIG. **115**B. This volume is defined by a depth of cutting and a smooth outer edge. By tracking the positions and/or orientations of the bur head **204**, femur **1672** and tibia (if tracked) during the procedure, the bur head **204** can be maintained within the boundary. Since the boundary is tied to the anatomy, tracking movement of the anatomy also tracks movement of the boundary.

Referring to FIG. **115**B, once the worn away area of bone **1674** and cartilage **1670** is reshaped, an awl **1680** or other bone punching or penetrating instrument can be placed through the access path in proximity to the bone **1674**. A tip of the awl **1680** is then poked into the bone **1674** in several spots to form microfractures **1681** in the bone **1674** and cause bleeding of the bone **1674**. This bleeding facilitates the growth of a layer of material over the bone **1674** that replaces the missing cartilage to reduce pain. A separate tracking device **1682** with markers **1684** could be associated with the awl **1680** to track a position of the tip of the awl **1680**. As a result, the microfractures **1681** can be placed at predefined depths in the bone **1674** and at predefined spatial locations in relation to one another to form a predefined pattern of the microfractures **1681**. In some embodiments, as an alternative to the awl **1680**, the bur head **204** could be replaced with a smaller diameter tip (e.g., smaller diameter bur head similar in diameter to awl tip) to drill a number of small holes instead of punching the holes with the awl **1680**.

Other knee arthroplasty procedures in which the instrument **200**, **1200** can be used includes mosaicplasty to treat focal cartilage defects, other ligament repair or reconstruction, removal of bone defects, and the like. A similar procedure employed for ACL repairs as described above could be employed for PCL repairs and repairs of other ligaments that stabilize joints.

In a mosaicplasty procedure, cartilage from an undamaged area of the joint is moved to the damaged area. So, in the focal defect described above, instead of AMS, the focal defect could be repaired by boring a small hole in the femur at the focal defect with the bur head **204** and then filling this hole with a plug of bone/cartilage from an undamaged area. The system **100** could be used to ensure that the depth of the hole is such that when the plug from the undamaged area is placed in the hole, the cartilage surface of the plug is flush with the cartilage surrounding the hole. The system **100** could also be used to ensure that the diameter of the hole is such that the plug has a predefined interference fit with the hole or a predefined tolerance to receive cement or other adhesive to secure the plug in position.

The system **100** and instrument **200**, **1200** could also be used to mill pockets in bone for purposes of receiving an implant. As shown in FIG. **116**, a receiver/stimulator **1700** of a cochlear implant **1702** can be placed in a pocket **1704** milled in skull bone **1706**. As with the prior described embodiments, a boundary could be established in the system **100** that defines the pocket **1704**. The bone **1706** could be tracked along with the bur head **204** so that the bur head **204** is maintained in the boundary to only cut the desired size and shape of pocket **1704** needed for the receiver/stimulator **1700**.

A tracker **1708** with markers **1710** could be mounted to the bone **1706** for purposes of tracking the bone **1706** with the system **100** and for registering the bone **1706** to pre-operative MRI or CT scans taken of the bone **1706**. By tracking the positions of the bur head **204** and bone **1706** during the procedure, the bur head **204** can be maintained within the boundary. Since the boundary is tied to the anatomy, tracking movement of the anatomy also tracks movement of the boundary.

Pockets could also be created with the instrument **200**, **1200** for other types of implants including neurostimulators, deep brain stimulators, and the like.

Rotating speed control of the bur head **204** may be employed in certain surgical procedures when cutting tissue such as bone. For instance, in the FAI procedure described above, the bur head **204** (e.g. bur head) may be controlled by the system **100** so that the speed of the bur head **204** is reduced as the bur head **204** approaches the acetabulum. Furthermore, the speed of the bur head **204** can be reduced as the bur head **204** approaches sensitive anatomical tissue. In yet other embodiments, the rotating speed may not be affected until the bur head **204** deviates from the home position.

Therefore, it is an object of the intended claims to cover all such modifications and variations that come within the true spirit and scope of this invention.

What is claimed is:

1. A method of performing a fusion procedure on a spine of a patient with an instrument having a hand-held portion, a working portion movably coupled to the hand-held portion and comprising a cutting accessory, a plurality of actuators operatively coupled to the working portion, a drive mechanism coupled to the working portion, and a tracking device of a navigation system attached to the hand-held portion, said method comprising the steps of:

determining a position of the cutting accessory relative to a virtual boundary defining a volume of tissue to be removed from the spine of the patient;

rotating the cutting accessory of the drive mechanism about a rotational axis; and

moving, with the actuators, the working portion relative to the hand-held portion in at least three degrees of freedom to substantially maintain the cutting accessory in a desired relationship to the virtual boundary as the hand-held portion is freely held and moved during the fusion procedure to remove said volume of the tissue from the spine of the patient with the cutting accessory.

2. The method of claim **1**, wherein the step of moving, with the actuators, the working portion relative to the hand-held portion in at least three degrees of freedom further comprises translating the working portion relative to the hand-held portion.

3. The method of claim **2**, wherein the step of moving, with the actuators, the working portion relative to the hand-held portion in at least three degrees of freedom further comprises translating the working portion relative to the hand-held portion along the rotational axis.

4. The method of claim **2**, wherein the step of moving, with the actuators, the working portion relative to the hand-held portion in at least three degrees of freedom further comprises pivoting the working portion relative to the hand-held portion in pitch and yaw about a pivot.

5. The method of claim **1**, wherein the virtual boundary defines a portion of a lamina of a vertebra of the spine with said method further comprising removing the portion of the lamina with the cutting accessory to provide access to an intervertebral disc of the spine of the patient with the actuators moving the working portion relative to the hand-held portion to substantially maintain the cutting accessory in the desired relationship to the portion of the Lamina.

6. The method of claim **1**, wherein the virtual boundary defines at least a portion of an intervertebral disc adjacent a vertebral body of the spine with said method further comprising removing the portion of the intervertebral disc with the cutting accessory with the actuators moving the working portion relative to the hand-held portion to substantially maintain the cutting accessory in the desired relationship to the portion of the intervertebral disc.

7. The method of claim **1**, wherein the virtual boundary further defines a desired shape of the endplates of adjacent vertebral bodies of the spine, said method further comprising shaping the endplates to the desired shape with the cutting accessory with the actuators moving the working portion relative to the hand-held portion to substantially maintain the cutting accessory in the desired relationship to the desired shape of the endplates.

8. The method of claim **1**, wherein the virtual boundary defines pilot holes within pedicles of the spine with said method further comprising preparing pilot holes within the pedicles with the cutting accessory with the actuators moving the working portion relative to the hand-held portion to substantially maintain the cutting accessory in the desired relationship to the pilot holes.

9. The method of claim **8**, further comprising translating the working portion relative to the hand-held portion along axes of the pilot holes to move the cutting accessory along the pilot hole axes and control depths of the pilot holes.

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